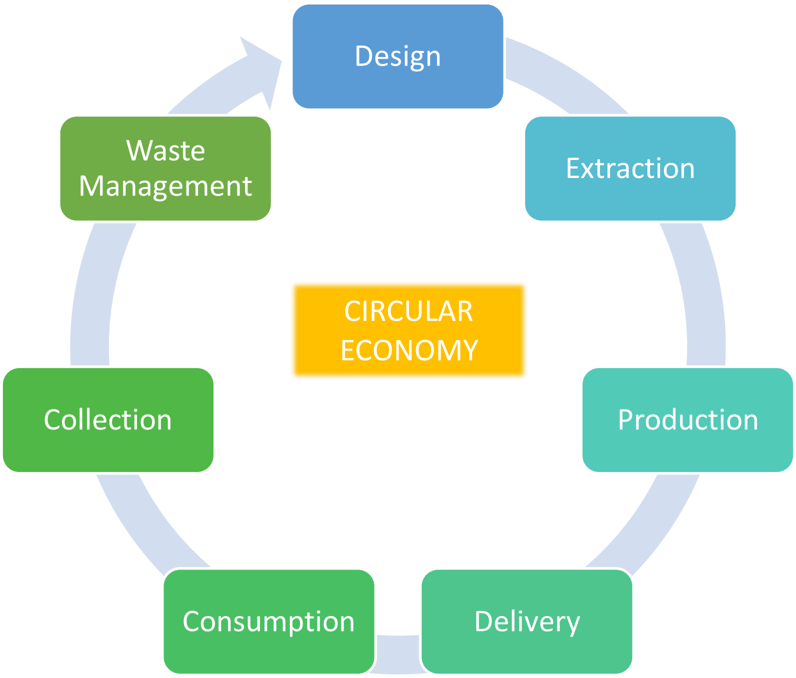
Design
Extraction
Production
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Consumption
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Waste Management
CIRCULAR ECONOMY

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AUTHOR: **Minh-Nhat Pham**

SUPERVISOR: **Professor Peter Breuhause**

TITLE

A CHAIN OF METRICS TO EVALUATE MATERIAL PERFORMANCES IN CIRCULAR ECONOMY – MATERIAL CIRCULARITY, LONGEVITY, RETAINED EMISSION, ENERGY, AND CHILD LABOUR

SUBJECT WORDS/ KEY WORDS: Circular economy, indicators, metrics, material circularity, metal, longevity, retained emission, retained energy, child labour

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SUMMARY

Although growth is seen as the main purpose of every economy, its consequences are vast and painful to the deterioration of environment. Circular economy has risen as a green transition of the international economy with the purpose of decoupling environment from growth. Thanks for this concept that waste of a supply chain is, once again, re-considered as input for the others. E-waste has been concentrated as one of the most important waste sources, since metals and materials from e-waste are mainly from non-renewable sources.

Under the umbrella concept of circular economy, several indicators have been formed to measure the performances of a huge number of elements, such as waste management, End-of-Life treatment, sustainability consumption, etc. However, regarding circularity and longevity as two of the main viewpoints of the concept, only two set of indicators are present until now. The purpose of this thesis is to create the third chain of metrics – the Material Circularity Metrics Chain – measuring circularity and longevity of material within the economy, which both former indicators could not achieve to estimate. The study hypothesizes that with recycling and refurbishment strategies, metals in products are circulated within the technosphere until they become obsolete. Returned products are assumed to be refurbished or recycled, thus prolonging the lifetime of metals and materials within the economy. Besides, the chain of metrics also estimates the retained emission and saved energy of the two waste management strategies, since recycle and refurbishment steps do not require as much energy and release as much emission as the mining-quarrying and production phases. Furthermore, to prove the linkages of economy and environment to society, the metrics chain calculated the amount of retained child labour working hours from circulated metals. This is believed to be the first group of indicators that can measure child labour working hours per gram of metals. Circular economy concept has reinforced the willing of maintaining metals in the economy, hence decreasing child labour.

Answers for the research questions are written in the theory part, yet an average smartphone is given as the pragmatic example. The results are in line with the theory that when metals can circulate more, material lifetime is prolonged, emission and energy are saved, and child labour is retained significantly. It is important that to achieve the goal, more efforts are needed to increase the returned of used products for waste management.

ACKNOWLEDGEMENT

This thesis is a leap for me from my comfort zone of sticking with scrutinizing sustainability with its social science aspect to its natural science field. The topic was found when my interest turned into the new concept of circular economy and how to apply the concept into practice.

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Last but not least, I want to save all my whole-heartedly gratitude to my parents and my grandmother, who have been trying to support me in many aspects of my life. Without them I could not have reached this far in life.

Table of Contents

ABBREVIATIONS

4WRI	4 WEEE Recycling Indicators
ASM	Artisanal Small-scale Mining
BIR	Bureau of International Recycling
C2C	Cradle-to-Cradle
CEIP	Circular Economy Indicator Prototype
CEPI	Circular Economy Performance Indicator
CET	Circular Economy Toolikit
CM	Combination Matrix
EESC	European Economic and Social Committee
EMF	Ellen MacArthur Foundation
EoL	End-of-Life
ILO	International Labour Organization
IoT	Internet-of-Things
ITU	International Telecommunication Union
LCA	Life Cycle Analysis
LI	Longevity Indicator
MCI	Material Circularity Indicator
MCMC	Material Criticality Metrics Chain
MFA	Material Flow Analysis
MRI	Material Recycling Index
PLCM	Product-Level Circularity Metric
UNEP	UN Environment Programme
WEEE	Waste electrical and electronic equipment

ANNOTATIONS

a	Fraction of returned products
b	Fraction of returned products entering refurbishment
c	Fraction of returned products entering recycle
C	Material Circularity within the economy
CL	Retained number of child labour working hours
d	Recycling ratio
em_1	Emission of material of the first cycle
$em_{consumption}$	Emission of material in consumption phase
$em_{extraction}$	Emission of material in extraction & purification phase
$em_{production}$	Emission of material in production phase
em_{RC}	Emission of material in the whole recycling strategy
$em_{RC\ step}$	Emission of material in the recycling steps
EM_{RC}	Retained emission of the whole recycle strategy
em_{RF}	Emission of material in the whole refurbishment strategy
EM_{RF}	Retained emission of the whole refurbishment strategy
EM_{RF+RC}	Retained emission of both recycle and refurbishment strategy
en_1	Energy needed for material in the first cycle
$en_{consumption}$	Energy needed for material in consumption phase
$en_{extraction}$	Energy needed for material in extraction & purification phase
$en_{production}$	Energy needed for material in production phase
en_{RC}	Energy needed for material in the whole recycling strategy
$en_{RC\ step}$	Energy needed for material in the recycling steps
EN_{RC}	Retained energy of the whole recycle strategy
en_{RF}	Energy needed for material in the whole refurbishment strategy
EN_{RF}	Retained energy of the whole refurbishment strategy
EN_{RF+RC}	Retained energy of both recycle and refurbishment strategy
H	Number of child labour working hours needed to extract 1 unit mass of material
L	Material Longevity within the economy
LA	Material longevity of the first original cycle
LB	Material longevity of refurbished product

L_C	Material longevity of recycled product
M	Total mass input of material
n	Total number of cycles
N	Material circularity within the product
N_A	Material circularity of the first original cycle
N_B	Material circularity of refurbishment
N_C	Material circularity of recycle
p	Factor which illustrates the end of material circulation after the 1st cycle or multiple cycles of refurbishment
P	Total production by children in 1 year
r	Factor which illustrates the relationship of the last insufficient amount of material and the total input amount of material
T	Total working hours of total children in 1 year
u	The insufficient percentage of materials from waste treatment strategies
v	The percentage of products retained from refurbishment and recycle process after each cycle

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. Consumerism and Planned Obsolescence

The current global issue certainly is climate change (Paris Agreement, 2015), or in another way of speaking, anthropogenic distortion of the environment (Kolbert, 2014). There is a long line of literatures which criticizes the human impact on the ecosystem, starting with *"An Essay on the Principle of Population"* of Thomas Malthus (1798). He provoked a pessimistic idea of the imbalance between the exponential growth of population and the arithmetical growth of subsistence. Following this school of thought – the Malthusianism – is a range of remarkable literatures which also emphasize the negative aspects of population and economic growth on the ecology system (Hardin, 1968; Meadows et al., 1972; Daily and Ehrlich, 1992; Raworth, 2017), and thus call for a radical change in economic revolution. Between two factors of population and affluance, the exponential growth of our economies is primarily to blame (Schandl et al., 2016; Pham et al., 2020). From the postwar era until now, growth has been one of the most important issues in every economy, no matter what it costs (Daly, 2005; Raworth, 2017). As in the book of Daly:

> *"Indeed, economic growth is the most universally accepted goal in the world. Capitalists, communists, fascists, and socialists all want economic growth and strive to maximize it. The system that grows fastest is considered best."* (Daly, 1991: 8).

Not only does growth depict the strength of the economy, hence the imperial position of one nation, but it also creates political alliance, thus diplomatic dependence from its allies. The economies are expected to have growth because it is supposed to bring lobbying support for the politicians, financial profit for businessmen, employment for the society, and so forth (Raworth, 2017). Growth itself has been one of the most critical debate within the scope of environmental politics (McCormick, 2018). Growth was believed to bring the nation out of poverty, to create more millionaires and philanthropists, to provide jobs for the unemployed, and to increase life's quality. Indeed, growth has being seen as the real holy grail for nearly all the economic problems (Daly, 2005).

Although there are various fruitful results growth can bring, it still leaves behind several critical consequences due to the lack of sustainability in its essence (Meadows et al., 1972; Daly, 1991, 2005; Raworth 2017). Several studies have investigated the negative correlation between economic growth and environmental degradation (York et al., 2002; Liddle, 2011, 2013; Bargaoui et al., 2014; Dong et al., 2018). But in particular, what makes growth a negative factor towards the environment? For creating growth, the throughput of the economy needs to have faster speed, since even GDP is calculated based on the value of throughput that flows inside the economy (Daly, 1991, 2005; Raworth, 2017). To accelerate that speed, one needs to concentrate in not only the input factor – production – but also the output factor – consumption – of the process. Moreover, the balance between production and consumption requires to be kept so that economic throughput can achieve its best condition. Before the Second World War, there was a concept constituted by a French economist, Jean Baptiste Say, which claims the economy can consume all of its production (Packard, 1960; Hall and Klitgaard, 2018). The Say's Law also deduces that eventually production will meet consumption at an equilibrium point. Yet at the time when the law was constructed, poverty was still present all over the world, and Europe and America were still struggling themselves as the developing nations. In the postwar era, thanks to technological advancement that mass production was operated in a smarter system, which leads to the overabundance of products with fewer consumption willingness. However, growth has to be maintained since it is the biggest mission of the economy. Therefore, the idea of "unrecognized want" was founded, with a mere purpose of trying to stimulate the desire for more. When that consuming desire still cannot keep up with the pace of production, producers started a trick to boost more sales. They made things easier to be worn out, more vulnerable, and with shorter lifespan. This practice was started from early 20th century, and it was framed as "planned obsolescence" (London, 1932). Consequently, consumerism – or more abstract, the human greed – together with planned obsolesnce have been allegedly charged of bringing the biodiversity of the ecosystem on the way to the point of no return (Sołczak, 2013).

Nonetheless, consumerism solely will not alter the whole picture if it is solved, since the problem does not lie at the end-of-life (EoL) phase but also at its production phase (Park et al., 2006). For more than half a century, planned obsolescence has been discussed as the root of the puzzle. The concept was first mentioned in an economic proposal of Bernard London. In his work of "Ending the Depression through Planned Obsolescence", even though he stated that "*I am not advocating the total destruction of anything, with the exception of such things as are outward and useless*" (London, 1932: 2), the main idea was still concentrating to launch a mandatory due date for every product, a stamp scheme for financial return from the government for handing in the "force dead" products, and a tax scheme to fine those who do not. Under the lenses of London, wealth equals to high consumption; and this idea is still growing its root in the mind of global leaders (Whiteley, 1987). Although a few did agree with his good intention of bringing the economy out of depression, the remain did not approve of the whole viewpoint. Yet two decades later, after his proposal, planned obsolescence was applied systematically and progressively into the economy. In the report "The Great Lightbulb Conspiracy" of Krajewski and the documentary film possessing the similar name directed by Cosima Dannoritzer, planned obsolescence was raised as a problem since the 50s with the first case is believed to be the lightbulb of Phoebus Cartel (IMDb, 2010; Krajewski, 2014). With the endurance of the former lightbulb was more than 3000 hours, it was redesigned to be just from 1000 – 2000 hours, which created a huge pathway for selling new products in shorter periods. Following this example, engineers of many entrepreneurs were demanded to make things less durable and easier to be worn out and eventually disposed of (Packard, 1960; Whiteley, 1987; Wieser, 2016). Many other cases in the 1950s were recorded in the book "The Waste Maker" of Vance Packard with a wide range of industries, from timber to automobile, electric appliances to cosmetics (Packard, 1960). Planned obsolescence was hidden from societal discourse and the media by the industries for a long time through the ending of the 20th century, until the famous case of Apple's Ipod in 2006 (Strausz, 2006). The Ipod was designed with a battery which is irreplacable by the customers themselves. For replacing it, the owner has to pay 99$ for Apple, and the fee even exceeded the price of a new product. Therefore, not only planned obsolescence shortened the lifetime of the product but they also made the users to be more dependent on the producers. Although through a range of literatures (Whiteley, 1987; Sołczak, 2013; Zallio and Berry, 2017) there are different kinds of planned obsolescence such as "Built-in Obsolescence", "Dynamic Obsolescence", "Progressive Obsolescence", "Style Obsolescence", "Psychological Obsolescence", or three kinds of obsolescence defined by Packard as obsolescence of function, quality, and desirability (Packard, 1960), there is an overwhelming consensus that the general terminology – planned obsolescence – has fastened up the resource consuming process by reducing product lifetime (Packard, 1960; Glaubitz, 2011; Sołczak, 2013; Wieser, 2016; Pineda and Salmoral, 2017; Satyro et al., 2018).

1.2. Byproduct of the linear economy – waste.

A critical common point between consumerism and planned obsolescence is that economic development is constituting a throw-away culture (Packard, 1960; Whiteley 1987).

To achieve the most pivotal mission of the nation, people have been encouraged to cast off things while their usefulness still remain. As quoted in "The Waste Maker":

> *"We are inundating ourselves with junk. Science devises junk; industries mass-produces it; business peddles it; advertising conditions our reflexes to reach for the big red box of it. To be sure, we are skilled junkmen – but what of us? How far have we advanced? We are junk-oriented cavemen!"* (Packard, 1960: 63).

For centuries the perspectives towards waste were shifted. Historically, before the Industrial Revolutions, waste mostly consists of human and animal excrement which were seen as a precious source of organic nutrients for the soil (Smil, 2017). At this time agriculture was the main factor for economic growth, thus the number of big cities was scarce. People still lived scattered for cultivation. Thus, waste was not dumped but reused to recapture all the value it brings. However, from the First Industrial Revolution, due to the rise of mass production that formal rural farmers gradually moved to live and work in big cities. The rise of population cumulation combining with inappropriate waste management had nurtured diseases such as cholera. Hence, for improving public health, both organic waste and industrial waste was relocated outside the city centers by underground pipes (Raven, 2007). Consequently, from the foundation of modern metropolitan that waste implies a negative image (Backes, 2017). Furthermore, planned obsolescence itself exaggerates the valueless utility of modern waste. For many decades, consumers have been drugged by the marketing idea of using a brand-new product will induce higher utility; since the updated version not only performs better but also delivers an advanced societal appearance for users (Packard, 1960; Whiteley, 1987; Wieser, 2016; Zallio and Berry, 2017). This built-in impression carries a mutual interaction between the consumers and producers, thus extending waste amount exponentially. The wasted value of what is being called as waste has increased exponentially, which creates a momentum to retain the value (Green Alliance, 2014). Based on the reports of Ellen MacArthur Foundation (EMF) – a private organization promoting circular economy, forgotten value embedded in what we call as "waste" has struck a dreadful degree. It has been estimated that the world lost yearly 460 billion USD of textile waste (EMF, 2017a), 1,000 billion USD of food waste (EMF, 2019), 80 – 120 billion USD of plastic waste (EMF, 2016a), and 44,7 million of tons of e-waste (EMF, 2017b). Among the waste sources, waste electrical and electronic equipment (WEEE) has been one of the most hazardous waste and the most complexed waste to handle (Ongondo et al., 2011). As written in the book "Recycling": *"E-waste, waste coming from electronics, is a mess,* *materially… E-waste is currently the fastest-growing waste category in the world”* (Jørgensen, 2019: 121). Moreover, WEEE contains a range of non-renewable resources and rare earth materials, which are in shortage because of consumerism in the last decades. Since we are entering the era of Internet-of-Things (IoT) that it is in utmost significance of having a right framework for WEEE treatment. This is the time for redesigning the vision of waste.

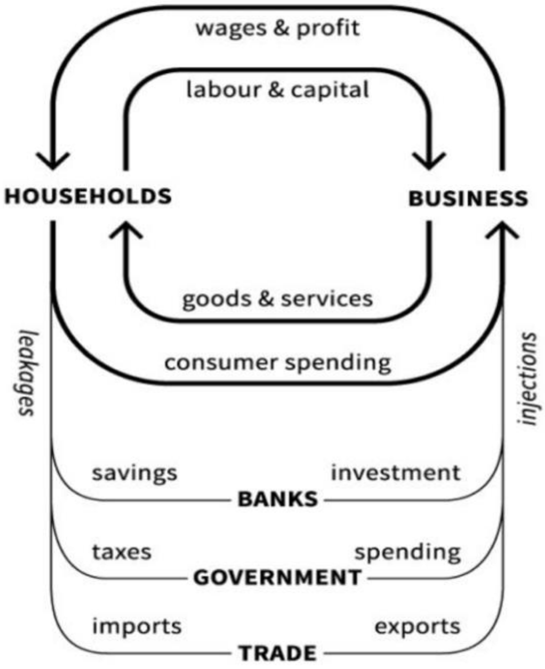


Figure 1: The Circular Flow diagram (from Samuelson 1948) (Raworth, 2017: 64)

It is due to the combination of marketing throw-away lifestyle and shortening product lifetime that this condemning economic culture has been causing huge burden on the environment, as the waste it creates cannot return much in value (McDonough and Braungart, 2002). There are several terminologies for this production – consumption pattern, such as the take – make – use – waste or the “linear economy” as it was entitled recently (Kalmykova, 2018). Linear economy is merely the result of the neo-classical economic theory which is widely taught globally (Fischer et al., 2018). The problem of the well known theory lies in its famous Circular Flow Diagram of Samuelson (Raworth, 2017) and the Cobb-Douglas production formula (Hall and Klitgaard, 2018). The famous diagram (Fig. 1) was redrawn for several times in different economic textbooks, yet it does not predict exactly the nature of economic activities. First of all, the diagram did not mention the existence of natural capital at the first place but only labour (human beings) and capital (financial resources). Later, although many following neo-classical economists did update the explanation of the diagram, yet the theory still ignores the limitation of natural resources for production input, the existence of energy within labour and manufacturing process, and the presence of waste as post-consumption product (Raworth, 2017; Fischer et al., 2018; Hall and Klitgaard, 2018). Therefore, to find another pathway as the contradiction for the linear economic culture, a range of different concepts yet possessing a common goal of redesigning economic theories have been brought to life, which eventually founded the “circular economy” (Murray et al., 2017). Circular economy acknowledges resource restraint, energy transformation, waste recognition, and hence possesses inside itself the ideal function of recirculating value of products and services and helps to decouple growth from environmental extraction and utilization (EMF, 2013). This concept acknowledges waste as an invaluable source of energy and material, hence reshape the appearance of waste.

Among several pivotal elements of circular economy concept, two main building blocks are focused scrutinized. Considering the limitation of natural resources, the exponential growth of consumerism by planned obsolescence, and the unchecked buildup of waste that this research pays more attention in applying and advancing a metric to prolong product circulation and lastingness. Product life extension not only plays a decisive role in battling planned obsolescence but also acts as a classic mechanism to reduce obsolete waste, to close the material loop of production – consumption and to relieve the burden of environmental degradation (Linton and Jarayaman, 2005). Furthermore, the value of resources will be utilized in a longer period of time due to resource circulation, thus improving and increasing the utility of the product.

1.3. Research purpose.

This study decided to pursue the theme of circular economy since it attracts more attention, both by theoretical and practical researches. The concept itself is an advanced and transitional leap from renewable energy to regenerate and redesign economic thinking. It does not only solve other environmental issues that renewable energy cannot cover, such as re-enhance biodiversity, redesign products, renovate business models, and recapture the wasting value of the linear economy but also revise and repair the recycling problem of recent renewable technologies, like the electronic and material waste of solar panels and wind turbines. As a matter of fact, *"the metal intensity of renewable energy technologies is generally larger than that of fossil fuel based energy"* (UNEP, 2013b: 18).

Moreover, the study also addresses a dark and pressing problem that the green energy transition has not yet mentioned: child labor related to materials, which are considered as the pivotal elements of the renewable energy transition.

For the main purpose of circular economy is to maintain the utility and value of products and services within the economic loops (Ghisellini et al., 2016) that product longevity and material circularity are two of the utmost significant issues. Within the scope of this master thesis, the research examines the lifetime and circulation of the materials within a smartphone, of which methodology is based on the research of Franklin-Johnson et al. (2016) and Figge et al. (2018). A new set of indicators, which can be called as "Material Criticality Metrics Chain" (MCMC) is constituted to answer the questions of material circulation and lifetime extension. The study also contributes to the development of the iterative equations as the improvement in energy saved and emission conserved when the lifetime of materials is extended and the resources are circulated. Furthermore, representing for the social influence pillar from the sustainable development concept, child labor reduction per kilo of material recovered is also scrutinized in this thesis. Consequently, several policy implications will be mentioned, with also the debate of the relationship between longevity and circularity features within the circular economy umbrella concept.

1.4. Research questions

As the guidance of problem investigation, questions are given out to orientate research direction. Posed as the critical elements of circular economy concept, material circularity and longevity within the technosphere lie in the heart of this study. Furthermore, since there is a tight connection between sustainable development and circular economy (Kirchherr et al., 2017), other elements from social and environmental aspects are included. Below are the questions that need to be answered within this thesis:

a. How should material circularity be measured if product refurbishment and recycling treatments occur at the post-consumption phase?

b. How should material longevity be measured if product refurbishment and recycling treatments occur at the post-consumption phase?

c. How many times the material can stay inside the economy before being unrecoverable waste and obsolete?

d. How long the material can stay inside the economy before being unrecoverable waste and obsolete?

e. How much emission can be reduced when material recovery occurs?

f. How much energy can be retained when material recovery occurs?

g. How many hours of child labor can be avoided when material recovery occurs?

The thesis is structured as follows. In section 2, literature review about circular economy concept, its building blocks and indicators are scrutinized. Theory for Material Criticality Metrics Chain is formed in section 3, with section 4 as methodology for finding and applying data and section 5 as results computation and discussion. Section 6 provides the debate surrounds the mentioned elements of the new set of indicators, while section 7 concludes the thesis with policy implications and limitations of the study.

2. LITERATURE REVIEW

2.1. Circular economy concept development

Circular economy is an umbrella concept (Ma et al., 2014; Lacy and Rutqvist, 2015; Blomsma and Brennan, 2017; Milios et al., 2019; Kristensen and Mosgaard, 2020). Different definitions of circular economy has been made through a huge range of literature. Not only the linguistic approach has been made with the semantic and syntactic scrutinization (Murray et al., 2017) but also comprehensive researches for comparing and interpreting perceptions towards circular economy has been conducted (Kirchherr et al., 2017; Kalmykova et al., 2018; Parchomenko et al., 2019; Helander et al., 2019). According to these studies, the concept is linked with the basic 3 Rs – reduce, reuse, recycle – and then developed with other Rs – recover, refurbish, remanufacture, repair, redesign, etc. Furthermore, circular economy consists of two loops which are always mentioned as the spheres for valuable materials to be recaptured – biosphere and technosphere (McDonough and Braungart, 2002). Raworth also saw the parallel flows of both these spheres and described them as the "butterfly economy" (Fig. 2). Theoretically, technological and biological loops are considered as indefinite circular flows which give value for waste unlimitedly. Yet, practically, due to the Second Law of Thermodynamics that recycling process not only loses a part of materials but also requires additional energy for closing the loop, as much tight as it should be. Therefore, Fig. 2 addressed the lost of energy and material, even when both the loops are closed. Hence, waste from production and consumption were mentioned by Raworth, which the neo-classical theory ignored totally.

Additionally, circular economy is also the result of economic adaptation and adjustment to the goal of sustainable development, which not only have the environmental, economic, and social impact but also the temporal significance towards future generation. Among several definitions of the concept, this thesis adapts the nearly exhaustive definition from the thorough research of Kirchherr et al., 2017:

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro

level (city, region, nation and be- yond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." (Kirchherr et al., 2017: 224 – 225).

The definition consists of several attributes, from different scopes of circular economy application to its influence on the recent economic process and its fundamental goals towards sustainable development. For clarifying the transition from the linear economy to the circular economy, several indicators have been constituted, both in qualitative and quantitative methodologies (Linder et al., 2017; Cayzer et al., 2017; Helander et al., 2019; Howard et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019; Kristensen and Mosgaard, 2020; Rossi et al., 2020). Since it relates to all the sectors of the society, from social science subjects such as politics, economics and business to natural science fields like chemical engineering, material engineering, and industrial ecology, that it is nearly impossible to have an indicator for measuring all the aspects circular economy covers (Lacy and Rutqvist, 2015).

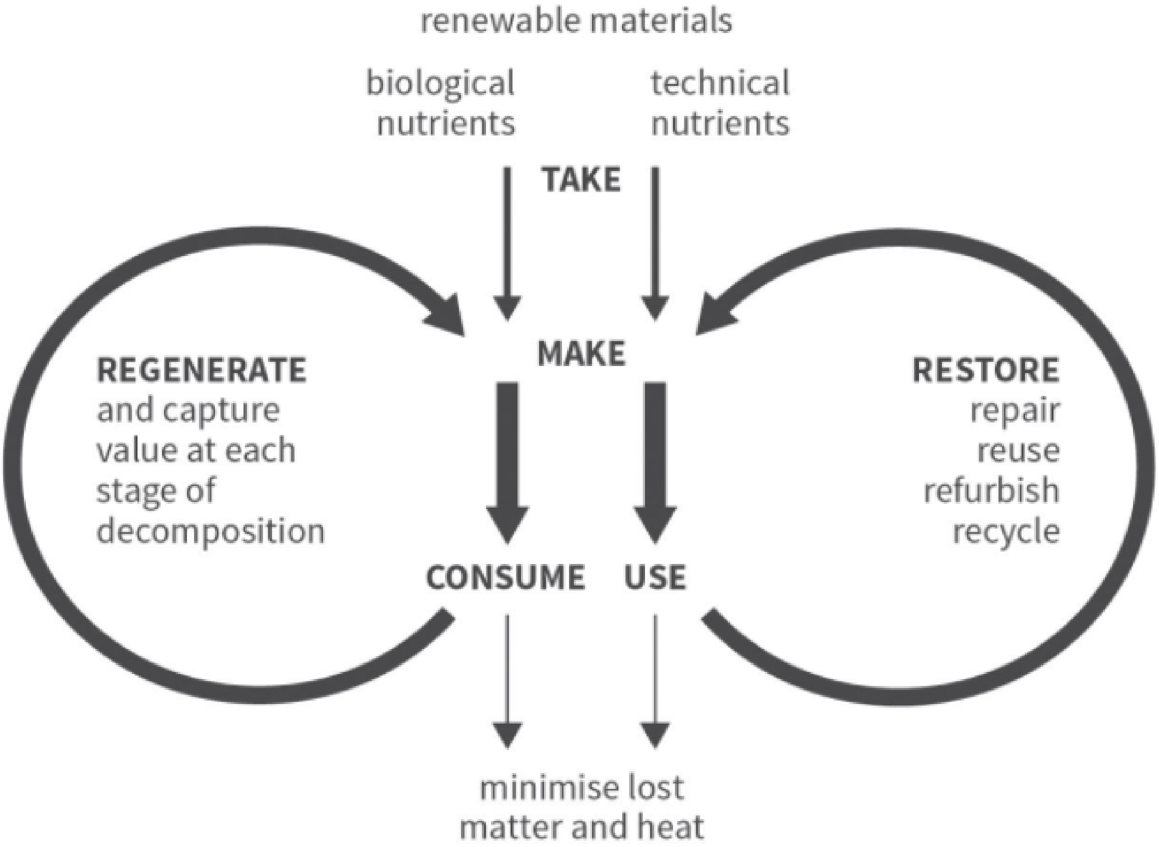


Figure 2: The Butterfly Economy (Raworth, 2017: 220)

To reflect some aspects of the academic development of circular economy, this literature review consists of four parts. First of all, the history of circular economy and other identical economic concepts are mentioned as the philosophical foundation for the umbrella theory. Secondly, various ways for breaking down circular economy in theory and practice are addressed as the way to have a deeper and clearer vision towards what the concept contains and embed. Thirdly, researches regard to product life prolongation are scrutinized to have an overal view of the impact it brings such as material conservation and utilization extension. Lastly, to quantify the performance of the circular transition happening within the current linear economy, several indicators are listed with the emphasis in metrics relating to product lifetime extension.

There are different perspectives, hence different definitions of circular economy and various ways of practices and applications (Ghisellini et al., 2016; Kirchherr et al., 2017; Kalmykova et al., 2018). However, several studies (Greyson, 2006; Pin and Hutao, 2007; George et al., 2015; Ghisellini et al., 2016; Korhonen et al., 2018) all determined that the concept of circular economy rose strongly in the second half of the 20th century, with the founded idea about the "Spaceship earth" of Boulding (1966). To contradict the image of the linear economy, or the "cowboy economy" with unlimited flow of resources and freedom of waste disposal, Boulding constituted the concept of the "spaceman economy". Imitating the harsh condition of resource shortage inside a spaceship, his idea was to create the economic concept in which its waste can be recycled, reused, and reproduced for the sustainability of the society (Boulding, 1966). Holding the same viewpoint, the ecological economist Georgescu-Roegen linked the question of what and how to constitute economical value of a product to the Second Law of Thermodynamics. This second law, or sometimes is termed as the Entropy Law, was understood as

"what goes into the economic process represents valuable natural resources and what is thrown out of it is valualess waste… From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of low entropy and comes out of it in a state of high." (Bonaiuti, 2011: 50).

Georgescu-Roegen emphasized that from the dawn of modern economics, men have been focusing so much in the limited low-entropy resources and thus "we have failed to acknowledge the entropic nature of the economic process" (Bonaiuti, 2011: 54). He proposed to form a new concept of "biophysical economy" as to emphasize the constraint of natural resources in economic growth. Following the Malthusianism school of thought, from 1977 Daly Herman published his book about the *"Steady-state economy"*. Holding the same expected result of conserving the ecosystem and protecting the environment, yet with a different viewpoint, Daly expressed his concept about the economy as the institution where it can sustain "constant stocks of people and artifacts, maintained at some desired, sufficient levels by low rates of maintenance "throughput"" (Daly, 1991: 17). Another remarkable work – "The Limits to Growth" – also mentioned and measured the negative impact of exponential growth to various sectors from agriculture to life expectancy (Meadows et al., 1972). Three scenarios were drawn out and within the boundary of finite resources, population and economy were tested with geometrical growth. Finally, two scenarios turned out to be incapable and one had an opportunity for a stable development. Recognizing the ignorance of worthy waste sources, the importance of industrial ecology in engineering was also considered critically (Frosch and Gallopoulos, 1989), or the significance of industrial metabolism for reviewing externalities in neo-classical theory (Ayres and Kneese, 1969) was also underlined.

The related economic concepts of circular economy were also constituted continuously with the "performance economy" (Stahel, 2010), "blue economy" (Pauli, 2010), and the "doughnut economy" (Raworth, 2017). Stahel Walter connected his concept to the circular economy with the agreement that circular economy measures wealth not by throughput as how the linear economy is seeing, but the quality and quantity of material stocks it contains. He founded the value-per-weight ratio as the unit to measure wealth creation in comparison to resource consumption. The more wealth can be created from the fewer resource used will be seen as effective production. Moreover, one of his profound persception is that customers concentrates truly not in the product but in the performing services that the product can bring. Hence, for supporting and enhancing sustainability, business models need to dive into the desire of performance from customers – their genuine insight. Stahel also discovered other metrics, such as the labour input-per-weight ratio to indicate the relationship of employment and resource extraction (Stahel, 2010). To propose more practical examples for rethinking and redesigning products, Gunter Pauli has researched various natural technologies that human beings have been learning from the ecology system, and then gave out the success of entrepreneurs who have adapted those green innovations (Pauli, 2010). Recently, a new concept of "doughnut economics" has emerged as the illustration of the biological boundaries for human societies (Raworth, 2017). The doughnut was drawn as the safe space for humanity to thrive sustainably, in which the society should not break the outer edge of planetary boundaries.

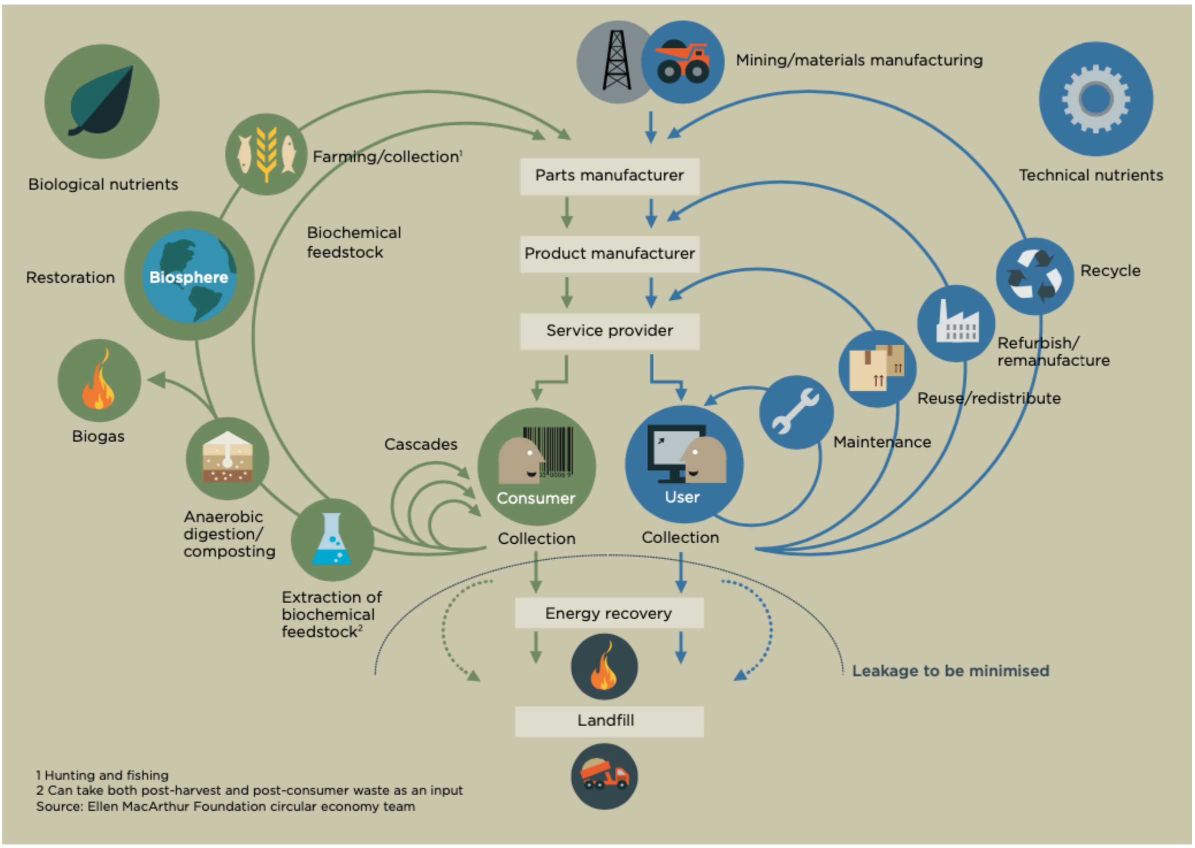
Although possessing the alike standpoint as the above mentioned economics theories, McDonough and Braungart took one step further into product redesignation with the concept of the two aligned material loops – biosphere and technosphere (McDonough and Braungart, 2002). Thanks to the loop establishment that circular economy got its advancement in material circularity. More ideas in how to rethink and redesign sources of energy has formed a fresh perspective in manufacture and production – "upcycle" (McDonough and Braungart, 2013). As products after initial use are often worn out, out-of-dated, and thus enter consequent short secondary lifetime or transform to another lessened and inferior products, upcycle encourages product designers to recycle the virgin products as a modern one which contains higher utility and offers better performance. The authors took the fight against the Malthusianist thinking of pessimistic conservative solutions, such as degrowth and de-consumerism, or the reduction of human activities. They lead the future engineers to change their cognition and develop a framework for upcycling their products from the beginning phase of production. Consequently, the amount of literatures recognizing the faults of neo-classical economics has risen massively through time, and all of them are a part of the foundation and enrichment of the circular economy.

Emerging as a pioneer in the circular economy research field, Ellen MacArthur Foundation (EMF) has devoted its mission and vision to accomplish a common platform for every socio-economic actors (EMF, 2013). The association is the first official insititute to publish comprehensive works regarding the circular economy concept (EMF, 2013), application of the framework in several countries, like India (EMF, 2016b) and China (EMF, 2018) and region such as the European nations (EMF, 2015a). The co-operation of EMF and other academic and business institutions also brought thorough reports about various subjects related to the biophysical economy, such as product design, plastic usage resolution, artificial intelligence, waste hierarchy, etc. (EMF, 2020). Thanks to EMF which serves as an intermediary actor that many corporations have acknowledged about the economic trend of the 21st century, leading to more domestic and international transitional changes.

2.2. Building blocks

As an umbrella concept, there is a divergence in translation of what the concept contains (Blomsma and Brennan, 2017). Under different lenses, the building blocks of circular economy are scrutinized and separated in various trends. First of all, since circular economy took its root from industrial ecology, ecological economics, and environmental economics that in the pessimistic Malthusianists' perspectives, three fundamental elements of the concept are the 3Rs – reduce, reuse, and recycle (Kirchherr et al., 2017). This three Rs lie at the foundation of waste management, which is also called as the waste hierarchy (Apitsz, 2010; Sakai et al., 2011; Pires and Martinho, 2019). The European Waste Frameword Directive interpreted the framework as the consecutive order in the field of waste management, which includes prevention, preparing for use, recycling, other recovery, and disposal (Pires and Martinho, 2019). According to the report PBL Netherlands Environmental Assessment Agency, "reuse" is literally defined as "*re-use by another consumer of discarded product which is still in good condition and fulfils its original function*", while "reduce" is semantically described as "*increase efficiency in product manufacture or use by consuming fewer natural resources and materials*", and "recycle" as "*process materials to obtain the same (high grade) or lower (low grade) quality*" (Potting et al., 2017: 15).

Several studies have chosen the Rs framework as the foundation of circular economy application guidance (Zhu et al., 2010; Ghisellini et al., 2016; Blomsma and Brennan, 2017). Furthermore, not only 3Rs but also 4Rs – with the additional factor of recovery – but also 6Rs with repurpose and remanufacture (Jihong and Chunhua, 2014), then 9Rs (Potting et al., 2017) with refurbish, repair, rethink, and refuse; or even using the Re-X as the abbreviation for combining end-of-life strategies and the environmental principles of value recapture (Sihvonen and Ritola, 2015). Therefore, the combination of prefix "Re" and classic supply chain phases is an acute consequence of transforming the linear economy to circular economy.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
Source: Ellen MacArthur Foundation circular economy team

Figure 3: The circular economy - an industrial system that is restorative by design (EMF, 2013)

The second method for dissecting circular economy components is to utilize the stages in the supply chain of linear economy and adapt them to the circular model. A wide range of literatures have focused in creating prevailing models for circular supply chain (Mihelcic et al., 2003; EMF, 2013; Kalmykova et al., 2018). Before the concept of biosphere and technosphere by McDonough and Braungart (2002) gained its academic reputation contemporarily, the circular model was drawn with circles going back in only one direction. Based on the waste hierarchy and the linear production – consumption patterns, Mihelcic et al. has depicted circular model as the tight loop consisting of different rings (2003). The inner circles are always preferred since they are reuse and remanufacture, while the outer rings are less considered methods, such as recycling and disposal. Both the studies of Mihelcic et al. (2003) and Kalmykova et al. (2018) utilized the circular models to scrutinize the environmental, economical and social benefits embedded. This circular economy depiction is in line with the fundamental thinking of biophysical economy, which inserts the small linear economy model into the large ecosystem boundary for repairing the negligence of neo-classical economics (McDonald and Patterson, 2006). Nevertheless, because of planned obsolescence and the rise of both technological advancement and consumerism that industrial design has almost payed no attention to sustainable and environmentaly friendly requirement in product design, which lead to the mixture of biological and technical nutrients. This poor and unplanned arrangement not only led to serious complication in waste management, like material and energy lost in recycling stage (Reuter, 2011; Schaik and Reuter, 2016) but also acted as a barrier in upcycling the waste and thus forcing the materials to re-enter the economy under a down-cycle condition. (McDonough and Braungart, 2002). Unexpected mixture of materials complicates the recycling phase – when materials are retrieved by dismantling, shredding, smelting, and metal refining (Reuter et al., 2018). With the material classification of Braungart from the 1980s (McDonough and Braungart, 2013), several literatures have accomodated their circular models with a distinct separation of biological and technical nutrients (Fig. 3) (EMF, 2013; Raworth, 2017). Braungart's resource distinction contributes much as a renovation in both product design and waste management. It reconstructs the way we develop environmentally friendly products and alleviates the complication of waste recycling and remanufacturing. Recently the two loops are seen as one of the main elements in circular economy design.

Another comprehensive methodology to inspect the core principles of circular economy is to address the biggest challenge of linear economy. The neo-classic model has done its good job in decreasing poverty by mass production and consumption, yet it has also caused mass amount of waste – the waste in the dreadful meaning of materials themselves. The book "Waste to Wealth" (Lacy and Rutqvist, 2015) breaks down the circular economy concept first by the waste categories the linear supply chain is creating: (i) wasted resources, (ii) wasted lifecycles, (iii) wasted capacity, and (iv) wasted embedded values (Fig. 4). After defining the wasted attribute to tackle, the innovative business model is formed based on the combination of technological advancement to gain circular advantages. 5 main business models, which are also addressed by other sources of EMF (2013), are (1) circular supply-chain, (2) recovery and recycling, (3) product life-extension, (4) sharing platform, and (5) product as a service. Together with the application of material engineering, artificial intelligence, waste hierarchy, systemization, and 3D printing that values of materials and services can be recaptured within the economy.

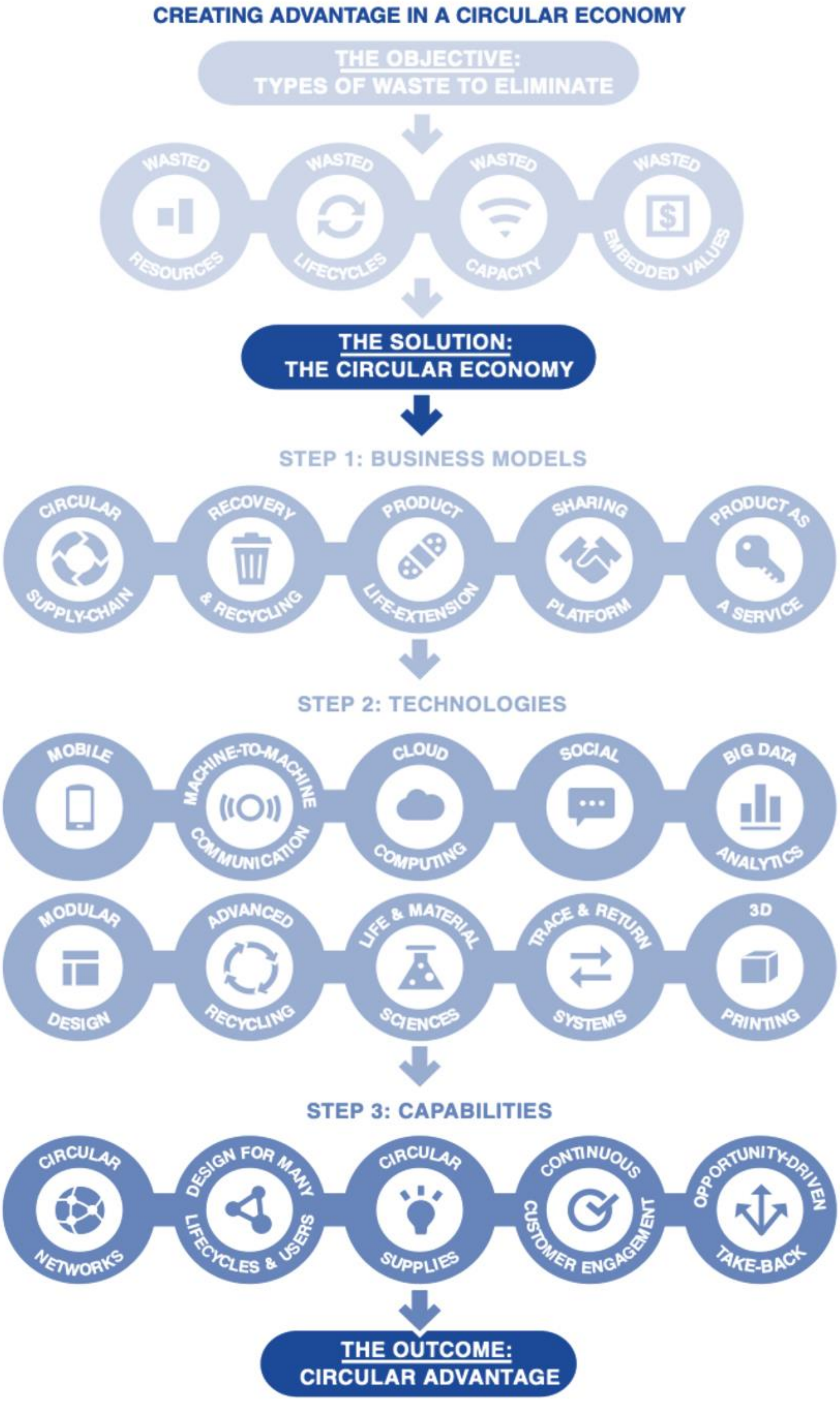


Figure 4: The circular advantage. (Lacy and Rutqvist, 2015: xxvi)

Until now there is still no consensus in all academic literatures of which structure should be the main framework for future studies of circular economy. The Re-X framework is considered the first distinctive step to get away from the linear supply chain. Thus, the huge amount of literatures related to the waste hierarchy can be considered the foundation of circular economy framework. However, the waste hierarchy expresses the disadvantages itself, since it does not address much the other innovative aspects of circular economy, such as state-of-the-art technological progression or the material classification, which are being addressed by the "butterfly model". The butterfly model can be recognized as the combination and renovation of waste hierarchy and material separation.

Nonetheless, circular business models, in which ingenious product and service designation is embedded, was not mentioned in the butterfly figure in a true and direct mean. Therefore, the circular advantage picture of Lacy and Ritqvist did address this lack of strategy. However, the latter chart (Fig. 4) is not yet the exhaustive model for the immense circular economy concept, since it does not mention the goal of sustainable development with 3 dimensions of social, environmental, and economic changes. The triangular interaction of three core sustainable development principles is graphed (Lieder and Rashid, 2016), yet it is still impossible to match other circular economy elements into the model.

Based on each perspective about circular economy and its critical attributes that different building blocks can be formed and models can be depicted. To form a comprehensive model, LCA and MFA method has been utilized. Figure 5 shows a circular economy model which is adapted from the model of Helander et al. (2019) about the flows of technological and biological nutrients within the circular economy. The red boundary expresses the unlimited solar energy that the atmosphere can receive, thus act as a main source of renewable energy for activities in both technosphere and biosphere. Circular economy, or the biophysical economy, acknowledges environment as the resources for production, consumption, and waste disposal. Thus, the economy takes its input from the environment, and give its output back to the environment. Minerals and materials are extracted from both the regenerated and non-regenerated sources of the environment, which then goes through material, components, and product manufacture. Due to globalization that finished products usually flow through service providers before reaching the customers. After serving its full utility in the consumption phases, following the circular economy attitude, products can be reused by other consumers, redistributed through service providers, taken back to the producers for reparation and refurbishment, or can be collected for recycling or remanufacturing. Nevertheless, within other specific products, repair and refurbishment do not return to the manufacturer but rebound to service providers. Generally, products after being used the first time can be returned back to the supply chain for starting its consecutive lifecycle. To illustrate the circular flows of technological nutrients, arrows and boxes are colored in blue, while black color indicates the waste from production, consumption, recycling, remanufacturing, and material extraction activities. These waste are seen as unrecoverable waste, thus going to landfill or incineration. The pool to hold these unrecoverable waste is called as final environmental load, since the waste is dumped into the environment without any other means of value recovery. Therefore, the less the amount of unrecoverable waste, the better for the economy. With biological nutrients, the flows and bozes are marked in green color. Food waste, mainly from consumers, can be extracted as biochemical feedstock to be transformed into energy (such as biomas) or into regenerated materials (such as fertilizer), which enters agriculture and aquaculture industries in a full cycle. Therefore, the model emphasizes the tightness and circularity of the loops within both spheres. Moreover, three pillars of sustainable development are also merged into the model. As economy and society connects closely to the technological sphere, and environment is the biosphere, that the circulated flows between two spheres are the real links to relate the three goals. Despite the effort of connecting different elements of circular economy, there are other elements that are not included in the graph.

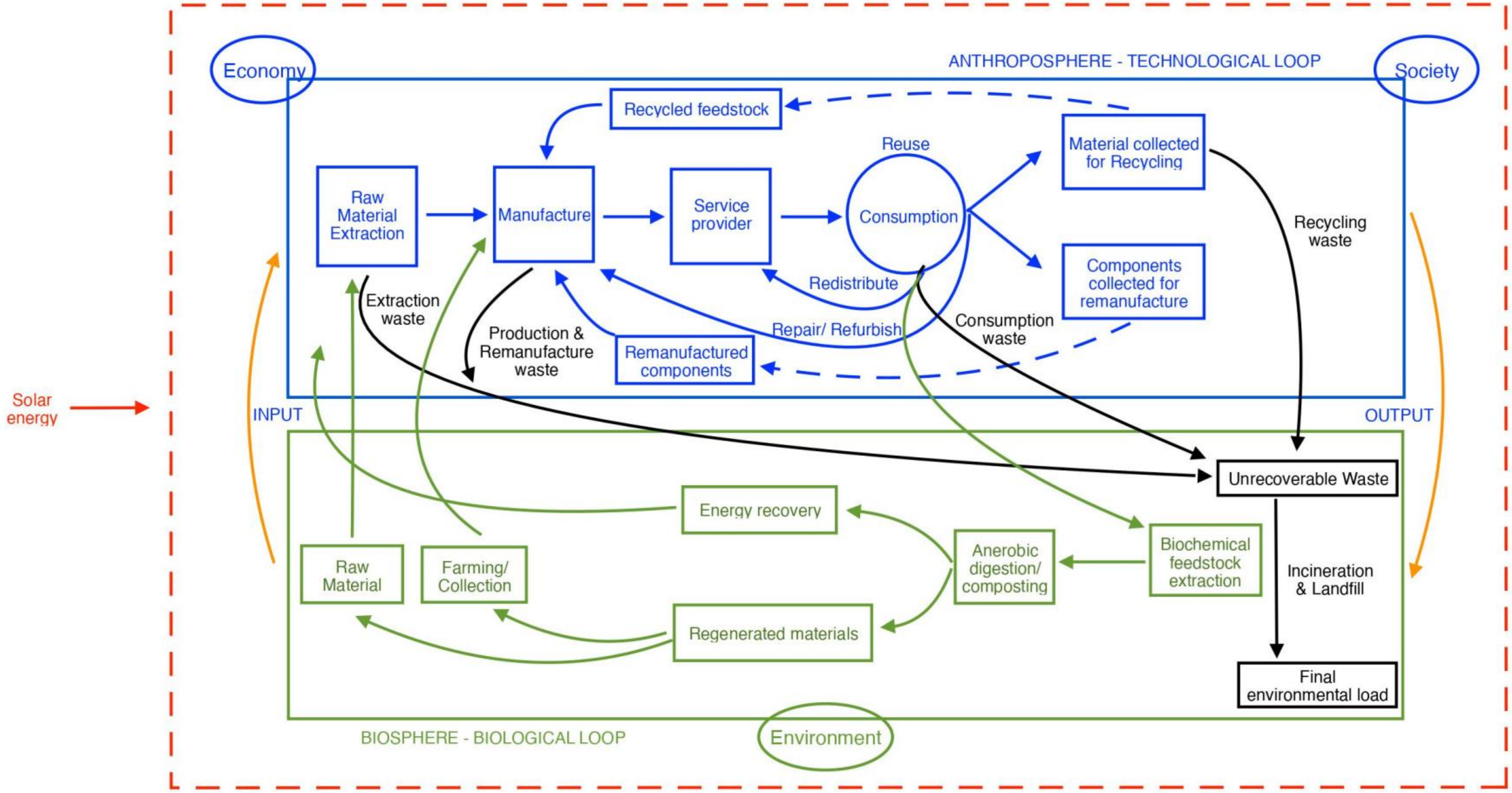


Figure 5: Systemic flow of biological and technological nutrients within the circular economy (Adapted from Helander et al. (2019))

2.3. Circular economy indicators.

To practicalize circular economy theory, numerous indicators have been constituted. It is demanding for all the socio-economic actors to measure the transitional change of the out-of-date economic theory to the up-to-date movement (Mihelcic et al., 2003). Without detail information and instruction, one cannot have the right direction for acting sustainably and producing – consuming cyclically. For the economic transformation to commence, decision-making requires quantitative and qualitative information which merely rely on the development of academic indicators (Gallopín, 1996). Indicators certainly is the foundation for national and international decisions, which eventually lead to economic, social, and environmental transformation. There are several definitions about indicators (Gallopín, 1996); yet with the common understanding, indicators are variables and its influence towards decision-making lies in how the variables are interpreted. According to Waas et al.:

> *"An indicator is the operational representation of an attribute (quality, characteristic, property) of a given system, by a quantitative or qualitative variable (for example numbers, graphics, colors, symbols) (or function of variables), including its value, related to a reference value."* (Waas et al., 2014: 5520)

Besides the term "indicators", other studies have mentioned the tool of conveying information under various terminologies, such as "parameter", "metric", "statistical measure", "variable", "measuring instrument", "index", or "piece of information" (Gallopín, 1996). Although bearing different names, the main purpose of the index is together with its reference, it conveys invaluable messages.

Several studies have reviewed diverse pools of circular economy indicators based on the inspection of the above mentioned terminologies (Helander et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Kristensen and Mosgaard, 2020; Rossi et al., 2020). Up to date, there is no indicator which can measure all the aspects of circular economy comprehensively (Kristensen and Mosgaard, 2020). Since circular economy possesses a vast coverage of academic fields that usually indicators are created to serve one or multiple purposes, yet not for measuring the whole umbrella concept. There are different methods to categorize the indicators. (about different kinds of categorization). Helander et al. evaluated the indicators based on the relationship between the reference of the metrics and their impacts on life cycle phases and material flows (2019). The authors investigated 10 indicators, containing some renowned indices such as the Material Circularity Indicator (MCI) (EMF, 2015b), Circular Economy Performance Indicator (CEPI) (Huysman et al., 2017), Longevity Indicator (LI) (Franklin-Johnson et al., 2016), and Product-Level Circularity Metric (PLCM) (Linder et al., 2017). Reviewed articles are separated into 4 groups following the life cycle phase: production, usage, End-of-Life (EoL), and across the phases. The study pointed out that not only the investigated indicators cannot cover all the circular economy concept but they also do not address the environmental sustainability much, since there is no metrics relating to the measures of environmental pressures. The impact on the ecosphere from the anthroposphere should be measured sufficiently, especially the pressures on footprint of land, air, water, and other types of emission. However, due to the reference of the indicators that it is nearly impossible to both cover the material management, waste management, and then environmental pressure in only one measure. However, there are other indicators used to measure the environmental pressures, such as carbon footprint, water footprint, wood footprint, etc. Needless to say, there is a necessity to have a set of indicators which can convey all the essential information about the circular economy. The idea was proposed in the study of Moraga et al. (2019). The study analyzed 20 micro-scale indicators which measuring the performance under the scope of product, service, or company. Since the definition of the modern economic concept is too broad, categorization framework of the article was based on 2 perspectives, the sensu stricto which only concentrates in the feature of slowing and closing resource loops, and the sensu latu which extends the application to business models and the sustainable development goal. Then the indicators are separated due to its relationship with technological cycles and life cycle thinking, and their references regarding to different circular economy strategies. The result also emphasizes in the lack of consideration for innovative business models and the possibility of one group of indicators to cover all strategies. Another research of Mesa et al. (2018) tried to create a set of indicators for product families, which can cover a range of circular economy strategies. Although the indices considered the linear flow of materials, reuse, recycle, reconfiguration, and other functional indices, this set still analyzes at the micro level and is limited at a product family. Pauliuk (2018) also created a pool of indicators which based on the life cycle assessment (LCA) and material flow analysis (MFA) methodologies. The group addresses many circular economy elements, both financial and non-financial issues, with various micro, meso, and macro sub-indicators (Pauliuk, 2018).

Since the circular economy concept takes the root from industrial ecology that physical linear flow model is often concentrated. Many indicators were built based on the product level assessment under life cycle analysis or material flow analysis methodologies. The study of Kristensen and Mosgaard (2020) has a pool of 30 micro quantitative indicators with the aim of categorizing the references of these metrics to three pillars of sustainable development. After sorting and scrutinizing the indices by different circular economy strategies, many of the micro indicators only underline the importance of the economy pillar and the environment pillar. The social benefit which can be brought by circular economic transition is quite neglected, especially with so few indicators have the ability to measure jobs creation, safe working environment, human rights, and social safety. Thus, the study urged for more weight balance towards measuring the effect of circular economy to the social development pillar. As also quoted, "*The Circular Economy clearly seems to prioritise the economic systems with primary benefits for the environment, and only implicit gains for social aspects*." (Geissdoerfer, 2017: 764). Moreover, although the micro indicators are well developed, there is still a lack of a common framework to measure micro level circularity due to the existence of multiple strategies within the umbrella concept. Parchomenko et al. have done an undoubtedly comprehensive review about 63 indicators. The authors grouped the indices by first categorized 24 circular economy elements mentioned in the reviewed articles. 4 clusters were identified by the Multiple Correspondence Analysis methodology, including the resource efficiency cluster – the biggest group, material stocks and flows cluster, product-centric cluster, and other-metrics cluster. Conclusively, the academic development of circular economy concept is at the stage of validity challenge period (Blomsma and Brennan, 2017), thus more debate will occur to achieve a common conceptualization and framework. Although there are a great number of indicators, most of the well developed indices concentrate in waste disposal, iterative resources usage, resource efficiency, and recycling efficiency (Parchomenko et al., 2019). Other elements are being neglected, such as the systematic prospects, value preservation, and product life extension. Furthermore, despite the fact that indicator has a role of convey vital information, the current measures – mainly micro level and product-based – are not much considered in the lense of politicians.

With an ambition to measure all the factors of the circular economy, the research of Rossi et al. (2020) constituted 18 indicators in total, including both qualitative and quantitative, to measure all three aspects of the circular economy which relates to sustainable development. Some indicator even include a number of sub-indicators, which consolidates the broad coverage of the concept. In the environmental aspect, indices to measure changes in raw materials, toxic substances, product longevity, and a range of Re-X strategies from waste hierarchy management. The economic aspect consists of parameters relating to cost reduction, revenue generation, taxation, and even circular investment. The social pillar includes metrics refer to job creation, stakeholder and employee participation in circular models, and client mindset (Rossi et al., 2020). Although it seems to cover nearly all the circular economy elements, due to confidentiality that the research does not provide detail information regard the equations, construct validity, reliability, and generality of the indices. Therefore, the linkages between the indices and their relationships of each pillar groups are ambiguous.

Consequently, through the comprehensive reviews about circular economy indicators, some main viewpoints should be considered solidly:

(i) The literatures of circular economy indicators have grown into a huge pool of measuring resources which can be applied based on the objective's scope, research methodology, research purpose, and research questions.

(ii) There is no single metric which can measure the total performance of the circular economy concept. A quintessential and consensual set of indices is in need for future conceptualization and framework formation.

(iii) Much of the indicators are still concentrate in the Re-framework, waste management, resource management, and economic efficiency. It is necessary to have more metrics which specify directly on the social impact by circular economy.

As the development of circular economy concept, creating a set of indicators - or a chain of metrics – to cover all its aspects requires huge effort. According to the scope of this thesis, the study devotes itself to two main segments of circular economy – circularity and longevity. Each aspect within the field can contain at least more than one metric, which can be used to compare the reliability, construct validity, and generality of the measures. Based on the above mentioned indicators review studies, the below listed metrics which are related to the Longevity Indicator (LI) of Franklin-Johnson et al. (2016) and the Combination Matrix (CM) of Figge et al. (2018) will be scrutinized and reviewed:

(1) Circular Economy Toolkit (CET)
(2) Circular Economy Indicator Prototype (CEIP)
(3) Cradle-to-Cradle (C2C)
(4) Product-Level Circularity Metric (PLCM)
(5) Material Recycling Index (MRI)
(6) 4 WEEE Recycling Indicators (4WRI)
(7) Material Circularity Indicator (MCI)
(8) Longevity Indicator (LI) and Combination Matrix (CM)

CET (Evans and Bocken, 2013) measures the sustainability in performance of the whole supply chain (Circular Economy Toolkit, 2020). Although there is no published academic article about CET, it is quite easy to have the access to the tool through its online platform. The tool provides 33 sub-sections for each supply chain stage, from the beginning of product design to the end of material recycling. However, the indicator is qualitative with trinary self-evaluated options only, as high (green color) – medium (yellow collor) – and low (grey color). Moreover, there is a huge amount of sub-sections related to recyclability of the product, yet there is not many encouraging the product lifetime extension. Besides the fact that user have to evaluate the sustainability of their businesses by themselves, the answers do not depict wide range of options and thus bringing the ambiguous conclusion to the user. Therefore, despite of high generality, there is no concrete evidence to support the construct validity and reliability of this indicator. The metric is analyzed as possessing weak consideration in the depth and detail of each circular economy element (Parchomenko et al., 2019), thus leading to the inapplicability in decision-making. Starting from the same perspective about measuring circular economy performance within companies and corporations with CET, CEIP is constituted with the same approach of building the evaluation of sustainable application through user's feedback (Cayzer et al., 2017). The indicator was built on the framework of Kingfisher Circularity Calculator, in which it follows with breaking down the lifecycle stages of the product and linking them with circular economy elements. Then, 15 questions were addressed in the semi-structured interviews with the answers are rated from linearity to circularity. The points for each questions form the total grades of the stage, thus adding to the total 152 scores of the scale. The higher the score the company can attain, the more circular the product is designed. Despite of having fewer questions than CET, the scale of CEIP supports the policy makers with deeper view about how sustainable their product is, hence assisting the employers to enhance the circular performance of the organization. However, based on the question list of CEIP, many circular variables are not mentioned, such as material recycling, environmental footprints, social impact of the sustainable product design, energy and waste from remanufacture and recycling, etc. The construct validity of the indicator is weak, since each question only concerns about the broad topic, such as bill of material is addressed, yet explicit concern about the toxicity and scarcity of the material are not mentioned. Reliability within the case of CET and CEIP is not easily reached due to the variation of interviewees' answers in different times. Moreover, no mathematical consideration about the data of products, materials, and emissions but only the numbers attached to how the questions are answered. Hence, although it still can assists the decision-making to some extent, there will be great need for other indicators which can measure more in detail the circular economy elements.

Different from other usual indicators, Cradle to Cradle (C2C) stands out as a thorough instrument which certifies the level of "goodness" of the material in the most crucial step – product design (McDonough Braungart Design Chemistry, 2016). The certification was created with the ambition of design product with 100% goodwill and fulfil all 5 main categories – material health, material reutilization, renewable energy and carbon management, water stewardship, and social fairness – which relates strongly to circular economy concept. According to the founders of C2C, the Re-X strategies only can help the industry to create less bad influence, thus it does not have enough power to create no bad but 100% good products. Hence, material health factor and social fairness were emphasized with equal importance comparing to other main circular economy principles. The metric possesses several temporal goals, with the short-term goal as clarification of bill of materials, the medium-term goal as positive design with efficient performance, aesthetics, material health, and material reutilization, and the long-term goal as "*a delightfully diverse, safe, healthy and just world, with clean air, water, soil and power - economically, equitably, ecologically and elegantly enjoyed*." (McDonough Braungart Design Chemistry, 2016: 3). The indicator will certify the materials within products by 5 levels: basic, bronze, silver, gold, and platinum. The higher and more precious the level, the more circular and better design the product possesses. Due to the complexity and comprehensive of the metric that heuristic calculation is not applicable but the product design process has to go through testing and examination. Comparing to CET and CEIP, C2C has much more detail and in-depth performance.

A huge amount of circular economy indicators focus on measuring stock and flow within the supply chain, and hence try to minimise waste and lost. However, there is one other way of constituting the metric with the consideration of economic value. Linder et al. have created an instrument to indicate circular ratio not by measuring material stocks or flows, or energy consumption and emission, but by the financial value of the materials used to build the product (2017). Based on the main circularity equation of their research, since the components of the product are disaggregated and multiply with their economic value that even when the price of recycled product parts are cheaper than of the virgin ones, higher presence percentage of the circulated parts within the product still enhance the circularity ratio. Because the authors tried to consolidate the construct validity of the indicator that its purpose is only to measure the circularity of the products, and not other circular economy elements (Linder et al., 2017). However, since the metric utilizes cost of the component as the base unit of analysis that price fluctuation will affect much the accuracy of the conclusion. Besides, confidentiality about the information regarding material procurement of different actors within the supply chain acts as the barrier of attaining enough data for computing circularity ratio. Moreover, circularity is only considered as the usage of recycled parts or materials, thus the indicator forgot to address other Re-X strategies, such as reused, refurbished, ands repurposed product’s component(s). Another limitation acknowledge by the authors is its assumption of similar lifetime between two products of the same kind. Therefore, circularity calculated by the PLCM in fact only measures a fraction of what material circularity defines. Nevertheless, the indicator has taken a new approach by calculating monetary value of the materials, which to some extent contributes to measuring the financial impact of circular economy.

Focus on a classic yet importance branch of material circularity, Reuter et al. have developed an indicator measuring recycling ratio of an immense range of non-renewable materials by computer simulation (Schaik and Reuter, 2016). The development of the Material Recycling Index (MRI) contains further benefits comparing to other indicators. Not only the circular ratio of the design is sketched out with detail percentage of recyclability but the result also reports the difference in circularity proportion of each individual material between designs. The conclusion about product recyclability is fashioned with a scale of 10 levels, from G as inefficient to A+++ as efficient in recycling resources. Then, each design will contain different circular ratios of different component materials with the scale from 0% to 100%, separated in 10 intervals of 10% each. Moreover, from the circularity level of the materials, the authors also discussed and instructed for product design improvement. Thus, the indicator provides clear information for decision-making and further researches about material recyclability. However, to receive the detail simulation and conclusion confidential data and bills of materials are required, which creates a particular barrier in metric applicability. Furthermore, for conducting the instrument, in-depth knowledge about LCA, MFA, and how to handle simulation tools are inevitable. Nonetheless, there is high level of construct validity, reliability, and generality of the indicator.

A set of indicators were formed to measure four main issues of WEEE recycling (4WRI) (Nelen et al., 2014): (i) weight recovery of target materials; (ii) recovery of scarce materials; (iii) closure of material cycles; and (iv) avoided environmental burdens. Normally, other indicators only measure how much recycling ratio of a material can achieve in weights, which often neglect the importance of material scarcity and recycling quality. For example, aluminium, gold, and silver have high percentage of recycling rates (European Commission, 2018a), but other rare earth elements which possess critically low recycling ratio are indispensable in electronic products. Moreover, material scarcity due to unbalanced geological and geopolitical also have a tremendous influence towards WEEE recycling rates. Therefore, Nelen et al. constituted the metrics to address the criticality of materials. However, to calculate material cycle closure rate, market price of recycled materials is utilized as a proxy for material quality. Although market price provides and reflects valuable information about the quality of materials, it also contains within itself the perspective of planned obsolescence, as the prices of recycled materials are usually lower than the prices of originally virgin ones. Thus, if there is another way to address material quality with the dismissal of planned obsolescence, the metrics will possess higher validity. Other ways to measure material quality after recycling are to calculate energy savings from recycling a material (Steinmann et al., 2019) and/or to compute the exergy loss of a material after recycle phase (Castro et al., 2007).

Reviewed by various articles (Helander et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019), Material Circularity Indicator (MCI) proves to cover several supply chain phases, from waste management to consumer utility and product lifetime extension (EMF, 2015b). The indicator concentrates in measuring circular ratio of the material from its virgin to reuse and recycling stages, with the explicit consideration about unrecoverable waste. From the data of material mass and waste, a linear flow index is created to observe how linear of the product design. Besides material’s physical features, the utility and lifetime of product built by that material are also taken into account for detecting the impact of socio-economical aspect and consumer behaviour on the circularity. Since the value ranges from 0 to 1, the less unrecoverable waste is counted the more circular the material can be. The guideline of the metric also provides different examples of company types and product groups, which improves the generality of the indicator. Although the indicator focuses on the physical aspect of the material, which leads to the lack of accounting monetary and energy value of material management processes, MCI still possesses high construct validity and reliability due to the clear explanation of metric formation and diversified examples. However, the lifetime element is used to compare between of the product and of the average industrial, which does not express explicitly how many cycles can the materials stay within the technological loop before turning all to unrecoverable waste. Nevertheless, the indicator requires confidential information of manufacturers, which are not easy to have access to.

Chosen as the foundation for this research, LI and CM hold in them a unique viewpoint towards the circular economy principles. Other indicators see circularity as "*the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product*" (EMF, 2015b: 19) or how much "tightness" of the circulation loop that the product can perform (Cayzer et al., 2017), which leads to the range of result as from 0 to 1 (or 0% to 100%). This type of unit measurement does not express how many possible cycles that the material can be present within the economy before it goes obsolete. To fill in this gap, circularity is defined as the number of times the material stays inside the economy (Figge et al., 2018). Furthermore, the exclusive factor that LI – and then CM as its developed instrument – aim to measure is product longevity element, which are not much debated or mentioned by other indices (Helander et al., 2019; Parchomenko et al., 2019). Thus, the authors of Combination Matrix focused in how to calculate the extended lifetime of the material when the product is refurbished and recycled. Although CE contains different core principles, its starting point is to keep the utility of material within the economy, avoiding unrecoverable and unusable waste. Thus, material lifetime extension – among with the strategies to ensure it happens and the benefits it brings later on – can be recognized as the essence of the CE model. Despite several instruments are made to measure circularity, among the above mentioned indicators and 63 reviewed metrics (Parchomenko et al., 2019), only the Material Circularity Index of EMF and the Longevity Indicator with its advanced edition as Combination Matrix did address the effect of product lifetime. MCI was not chosen as the methodology for answering the questions since the indicator does not provide clear results about product lifetime extension since it concentrates merely in material circularity. To answer the research questions of creating a new chain of metrics which scrutinizes the relationship between material circulation and product lifetime extension, the thesis develops the Material Criticality Metrics Chain (MCMC) to not only calculate circularity and longevity but also measure other relevant aspects: material recovery, energy preservation, emission diminishing, and child labor reduction.

3. THEORY

3.1. Research strategy

Circular economy indicators took their main roots from two main methodologies of industrial ecology: LCA and MFA (Corona et al., 2019). Since the life cycle assessment method is defined as

> *"an environmental accounting and management approach that considers all the aspects of resource use and environmental releases associated with an industrial system from cradle to grave. Specifically, it is a holistic view of environmental interactions that covers a range of activities, from the extraction of raw materials from the Earth and the production and distribution of energy, through the use, and reuse, and final disposal of a product"* (Curran, 2008: 359),

and the material flow analysis method is describes as

> *"a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material"* (Brunner and Rechberger, 2004: 3)

that the indices developed from these two methodologies covers a huge spectrum of stages and phases of the industrial economy. Although the concentration of LCA and MFA are still in the cradle-to-grave economy, the metrics rooted from them are designed for curbing down negative stocks and flows of the linear economy, and for recovering more material and value to achieve the circular transition. This transformation reflects the cummulative experience of social and natural scientists within the field of industrial ecology. Based on the theory of circular economy, constituted indices are also seen as theoretical framework for measuring one or multiple elements of the concept. The logic to inquire data collected from the real world and form them into theories is called *Induction* (Blaike and Priest, 2019). Established from the existent Combination Matrix**, the research strategy for forming a new and more thorough set of indicators of this study will also take *Induction* as its logic of inquiry**. Specifically, based on the study of Figge et al. (2018), some measurements related to preserved values are induced and added into the calculation to adapt with the wide sustainable development approach of the concept. Besides, the aims of the thesis are to "explore" product lifetime extension, "describe" to what extent does material recovery treatment benefits the environment, economy, and society, then to "predict" what are the most critical factors determine circularity and longevity of the material within products. Thus, *Induction* strategy will assist the research to be conducted in the right direction. After forming the equations, data are collected to exemplify the theory. Although the second step is a way of attesting the theory, deduction is not considered as the strategy of the thesis, since falsification takes time, effort, and multiple trials (Kuhn, 1970).

The number of circular economy indicators have amounted and accumulated for more than 2 recent decades. Despite the presence of both quantitative and qualitative indicators, **the set of indices within this research is constituted *Quantitatively*** because of several reasons. Firstly, since the questions regarding product lifetime, material recovery, and preserved values that qualitative research does not possess enough ability to measure them accurately. Without clear numbers, decision-making has to struggle with uncertainty, ambiguity, and vagueness in result interpretation. Secondly, the conclusion from some qualitative indicators such as CET and CEIP can be biased due to lack of industrial and technological knowledge of those who answer the survey and/or interview questions. Thus, the result can easily get into bias. On the contrary, the results of other quantitative indicators are obviously numbers, which are deduced from constructed equations. They are not much altered by feelings, personal opinions, and personal knowledge. Therefore, the indices will be formed according to what they are meant to measure, with different unit of measurements.

3.2. Research quality

In spite of the fact that a great number of metrics were established, not many authors self-evaluted the quality of their indicators. Some literatures did review and assess the degree of quality of several indices (Linder et al., 2017; Corona et al., 2019), such as their validity, reliability, generality, and transparency. Before forming the metrics chain to measure material circulation and endurance, desirable qualities are necessary as the indicator evaluation groundwork.

Reliability is considered as indispensable since it is the first interrogative thinking a scientist holds when approaching a new measure. One will simply ask oneself whether the conclusion will be the same if the method is conducted again, regardless of who operates it. In another way of speaking, "*reliability is the extent to which a measure is the same each time it is performed and by whoever performs it*" (Bannigan and Watson, 2009: 3238). To achieve the high level of reliability, the result of the indicator needs to be stable after repeated trials. Stability is one of the most crucial features of reliability, which can be reached by test-retest method. After re-attempt to conclude the result, if the value is still the same, then the indicator can achieve its stability, thus gaining the reliability status. Since *"stability indexes are most appropriate for relatively enduring characteristics such as personality, abilities, or certain physical attributes such as height"* (Polit and Hungler, 1995: 349), accurate numbers collected from open official data sources will be calculated as the application example, which eventually will yield high reliability. **Stability with test-retest reliability can also be conducted through comparing the metals within a same product to see the similarities and differences between various materials.**

Merely being reliable is not enough for the indicator to be useful. Accuracy of the measurements needs another factor to gain its quality, which is validity. Validity is considered to the extent that the indicator measures correctly the object that it is meant to measure (Bannigan and Watson, 2009). There are many questions surround the scope of measurement of an indicator. The metric needs to be designed so that it does not measure anything else than its purposes. Validity covers several sub-contents, such as face validity or content validity – the expression and formation of the indicator looks reasonable – and construct validity – the relationship between the metric being developed and the construct/ concept being investigated. **To gain face validity and content validity, the construction of the metrics chain will be described transparently. Moreover, the relationship between circular economy elements and the indicators is also connected tightly when formulas are written**, thus enhancing the construct validity of the metrics chain.

Nonetheless, other quality features are still in need, since *"validity is totally predicated upon reliability and reliability in itself is insufficient"* (Bannigan and Watson, 2009: 3238). Utility (Bannigan and Watson, 2009) or Transparency (Linder et al., 2017) are mentioned as another feature which a profound indicator should possess. Utility can be understood as *"how practical the scale is to used in the field"* (Bannigan and Watson, 2009: 3242), or how straightforward and accessible the indicator is. The more convenient the user feel when using the metric, the more utility the indicator can reach. It is crucial to identify the utility as an aspect of quality of the indicator constitution and the utility in economic terms as the usage benefits a product can bring. **To achieve high utility level, the metrics chain aims to express the formulas in clear language, with graphs and diagrams for easy scrutinization**. Moreover, the components of the equations are designed so that data to calculate the metrics is to some extent accessible.

3.3. Theory

3.3.1. Material circularity metric

The study proposes two different perspectives towards calculating the material circularity, which acts as the core of the metrics chain. Based on the study of Franklin-Johnson et al. (2016) and Figge et al. (2018), cannibalisation – the process of product disassembly and then material recycling – is seen as the end of the material circulation. Their circulation of the product stops after the product is recycles. However, according to the circular economy concept, material presence within the economy is one of the most decisive factors. The longer the material kept inside the technological loop the better for the environment, the society, and the economy. If material circularity is stopped at the time of recycling, then the metric only reflects part of a big picture. Therefore, from the framework of Figge et al., the study names their calculation as "material circularity within the product" and develop another calculation as "material circularity within the economy".

3.3.1.1. Material circularity within the product

The concept of circularity is defined differently according to the purpose of computation and calculation of the indicators. The MCI of Ellen MacArthur Foundation defined their circulation ratio as the minimalization of linear flow and optimization of circular flow of materials, with regard to the fraction of product's life expectancy and utility. As to answer the question of how many times the material can stay inside the economy with the advancement of the Re-X strategies, the definition of MCI does not provide enough information to satisfy the research question. Particularly, MCI addresses the circularity of materials in a percentage unit, which does not specify the circulation times of a particular amount of material before it goes obsolete. Following the work of Franklin-Johnson et al. and Figge et al., circularity is seen as the retention of material within iterative cycles (Franklin-Johnson et al., 2016) or *"the number of times a resource is used in a product system"* (Figge et al., 2018: 299). This perspective took its root from the works of Bailey et al. (2004, 2008). They proposed the calculation for circularity not as a percentage like other indicators have done but as the "path length", such as how many cycles a material can serve before it becomes unrecoverable waste and goes obsolete. Therefore, the thesis follows the framework of material circularity and longevity of Figge et al., and then develops it to a broader extension.

Material circularity has to be calculated following the material flow analysis. For the material to remain inside the economy, not only mineral extraction and product aggregation is necessary but also the End-of-Life (EoL) treatment of the resources is indispensable. Although several EoL treatment strategies are mentioned, such as repurpose, refurbish, reuse, recycle, and remanufacture, to be in line with the studies of Figge et al., the thesis also scrutinized two main flows: refurbishment (which includes reuse and remanufacture) and recycle. Repurpose strategy is not applied since normally product repurpose is seen as downcycle (Zink et al., 2014), a treatment which depreciates the original functional value of materials within a particular product. After serving the first cycle as virgin materials within original products, the products are collected for EoL treatment. Actually only a percentage of products can be traced back and recollected based on whether the company or the authority has any take-back program for that specific product (EMF, 2017b). The returned products then will be evaluated to conclude whether the products can go through refurbishment to serve the secondary life or they have to enter the recycling process. Therefore, to compute circularity of a specific material, three distinct parts are constituted in the work of Figge et al. (2018), including N^A as the circulation of the initial use, N^B as the circulation of the refurbishment process, and N^C as the circulation of the recycle process. Thus, we have material circularity within the product is computed as:

$$N = N^A + N^B + N^C \tag{1}$$

As the material serves upto its best of the functional value in the initial use phase (the 1st cycle) that:

$$N^A = 1 \tag{2}$$

With N^B, circulation of refurbishment process will be calculated as a fraction of all the products got returned (usually it is less than 1 or 100%) and multiply with the returned products which are selected to go through refurbishment. The fraction of returned products is a_j and the fraction of returned products go to refurbishment is b_j. If we call n as the number of cycles, then we have the equation as:

$$N^B = \sum_{i=1}^{n} \left[\left(\prod_{j=1}^{i} a_j b_j \right) \right] \tag{3}$$

Equation (3) illustrates the iterative cycles of the amount of materials within a number of products got refurbished consecutively after the 1st initial cycle. Therefore, after each time of return and refurbishment, the fraction gets smaller and smaller according to the percentage of returned and got refurbished products, which also lower the amount of materials within the economy in the downstream.

N^C is computed, according to Figge et al. (2018), with a correspondence of a geometric series. Since recycle is seen as the last step of material circulation in their lense that the variable (p) consist of two parts, one is the portion of returned products entering recycle process immediately after the 1st cycle, and the other is the portion of returned products, after some refurbishment cycles, getting into recycle phase eventually. The first part is computed as $(a_1 c_1 d_1)$ which c_i stands for the fraction of returned products getting into recycle process, and d_i stands for the percentage of recoverable materials, or the recycling ratio. The second parts demonstrates the fraction of products, after some refurbishment cycles, got collected and enter the recycle process. This second part is calculated as:

$$\sum_{i=2}^{n} \left[\left(\prod_{j=1}^{i-1} a_j b_j \right) a_i c_i d_i \right]$$

Therefore, the variable p which illustrate the end of material circulation after the 1st cycle or multiple cycles of refurbishment is computed as

$$p = a_1 c_1 d_1 + \sum_{i=2}^{n} \left[\left(\prod_{j=1}^{i-1} a_j b_j \right) a_i c_i d_i \right] \tag{4}$$

Since recycle circulation of a material is the remain part of initial circulation and refurbishment circulation that N^C is computed as

$$N^C = \frac{p}{1-p}(N^A + N^B) \tag{5}$$

in which $\frac{p}{1-p}$ is the geometric series, which *"shows the percentage of resourced that are recycled overall after an infinite number of cycles have been taken into account."* (Figge et al., 2018: 300).

We then attain the general formula for material circularity within the product:

$$\begin{cases} Circularity = N = N^A + N^B + N^C \\ N^A = 1 \\ N^B = (ab)\left[\dfrac{1-(ab)^n}{1-(ab)}\right] \\ N^C = \dfrac{p}{1-p}\left[\dfrac{1-(ab)^{n+1}}{1-(ab)}\right] \end{cases} \tag{6}$$

Assumptions are made in regard to the formation of this formula. First of all, to simplify the process, $a_i = a, b_i = b, c_i = c, and\ d_i = d$, regardless of the $i. (i = 1,2,..,n)$. In reallife situation, if the results of products returned and then enter the waste treatment processes are different each cycle, then this assumption does not hold, yet the calculation is still valid and applicable. Moreover, after products are returned, to serve the sustainable development goals, it is assumed that whether it will be refurbished or recycled. Thus, none of the returned products end after its first initial cycle, and therefore: $b + c = 1$.

Gold was chosen as an example for material circulation in the work of Figge et al. (2018). With the value of $a = 15\%$; $b = 65\%$; $c = 35\%$; $d = 95\%$; $n = 2$, refurbishing process contributes an additional of 10.7% in circularity and recycling process added a surplus of 6.06% in circulation of gold. (Figge et al., 2018: 303). In total, gold circulation within the product from their computation is:

$$N = 1 + 0.107 + 0.0606 = 1.1676\ (times)$$

3.3.1.2. *Material circularity within the economy*

Although Figge et al. (2018) has addressed material circularity in a new way, it still does not answer to the question of the circulation a material that can maintain when refurbishment and recycle are integrated into the EoL treatment of products. Based on the lense of *"cannibalisation"* of Figge et al. (2018), recycle is the end of material circulation, even if there is still a fraction of recoverable material, after being recycled, re-enter the economy. Therefore, material circularity within the economy is addressed in another approach.

If (a) stands for the fraction of returned products and (b) stands for the percentage of returned products chosen to be refurbished and thus gain its refurbishment lifetime, then (ab) results as the dedicated circulation of material in regard to refurbishment process. Likewise, if (c) is the percentage of returned products chosen to be recycled and (d) is the recycling ratio of a specific material, then (acd) results as the devoted circulation of material with regard to recycle process.

Holding the same material flow analysis yet if the perspective of material circulation completion should be achieved accurately, recycle is not the end of circularity but only a step to retain functional value of metals. Therefore, in the particular case when an amount of materials manufactured into a specific number of products, the following cycles are seen as the time when materials re-enter the economy, both through refurbishment and recycle phases (Fig. 7). The higher percentage the materials are preserved inside the technological loop, the more circularity they can contribute to the economy. After each cycle, returned products are put through evaluation for refurbishment or recycle again, creating an iterative times of material presence inside the economy. However, the latter the cycle can reach, the less former materials it can preserve, since percentage of return and the recycling ratio are not perfect (< 100%). Thus there will be the last cycle when the former-used materials of the 1st cycle are nearly obsolete (Fig. 6).

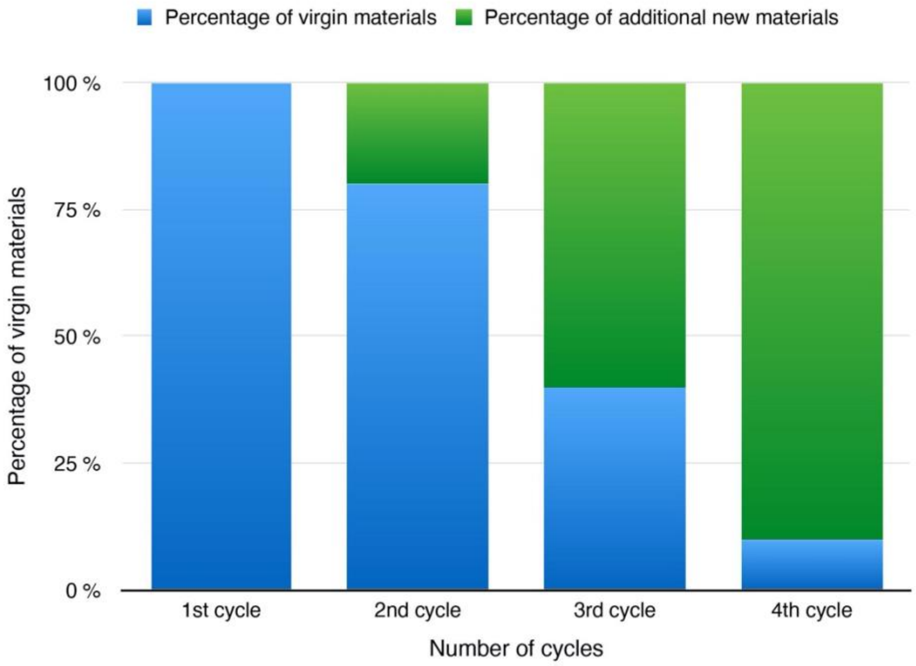


Figure 6: Examplification of decreased virgin material percentage after each cycle

Material circularity within the economy can be computed heuristically by counting the presence of material in each cycle, both from refurbishment and recycle. Assume that all returned products have to re-enter the economy through refurbishment or recycle process, after the 1st initial cycle, the percentage of re-circulated material in the 2nd cycle can be coalculated as:

$$ab + acd$$

with (ab) is the dedicated circulation of material from refurbishment process and (acd) results as the devoted circulation of material from recycle process. As to force the materials in products to re-enter the technosphere in the 3rd cycle, refurbished and recycled products from the 2nd cycle need to be returned again, and from those inventories, products are being evaluated again to go through refurbishment or recycle. Hence, in the 3rd cycle, we can achieve the circulation of material as:

$$(ab + acd)^2$$

The power of two implies the multiplication of the circulation from the 2nd cycle $(ab + acd)$ to the retreatment process of the 3rd cycle. If we compute heuristically material circularity of the 3rd cycle, then we can have (as in Fig. 7)

$$(ab \times ab) + (ab \times acd) + (acd \times ab) + (acd \times acd)$$
$$= (ab)^2 + 2a^2bcd + (acd)^2 = (ab + acd)^2$$

Apply this computation to the 4th cycle, then we can have the similar result of dedicated material circulation as:

$$(ab + acd)^3$$

Therefore, to generalize the achieved material circulation at the n-cycle from both refurbishment and recycle processes, we will have:

$$(ab + acd)^{n-1}$$

and to calculate in total the devoted the times of circulation an amount of material can be present within the economy (which can be called as C to differentiate with the N above), we can attain:

$$C = 1 + \sum_{i=2}^{n} (ab + acd)^{i-1} \qquad (7)$$

with i denotes the ordinal cycle and n denotes the total number of cycles. The reason of $i = 2$ because the initial cycle is counted as the 1st cycle, so recycling and refurbishing activities happen at the beginning of the 2nd cycle. Equation (7) is valid since if there is no refurbishment or recycle treatment, then $a = b = c = d = 0$. If the product is only refurbished and not recycled, $c = d = 0$; and vice versa, $b = 0$. Because the idea of material circulation within the economy does not follow cannibalisation concept from Figge et al. (2018) that materials will end its circulation in 2 cases, whether the products are lost/ not returned (thus $a = 0$) or the material goes obsolete after being through several cycles. Although lost products still physically keep the materials inside the economy, it does not push the materials to the flows of refurbishment and recycle, thus leading to utility lost or functional obsolescence of materials.

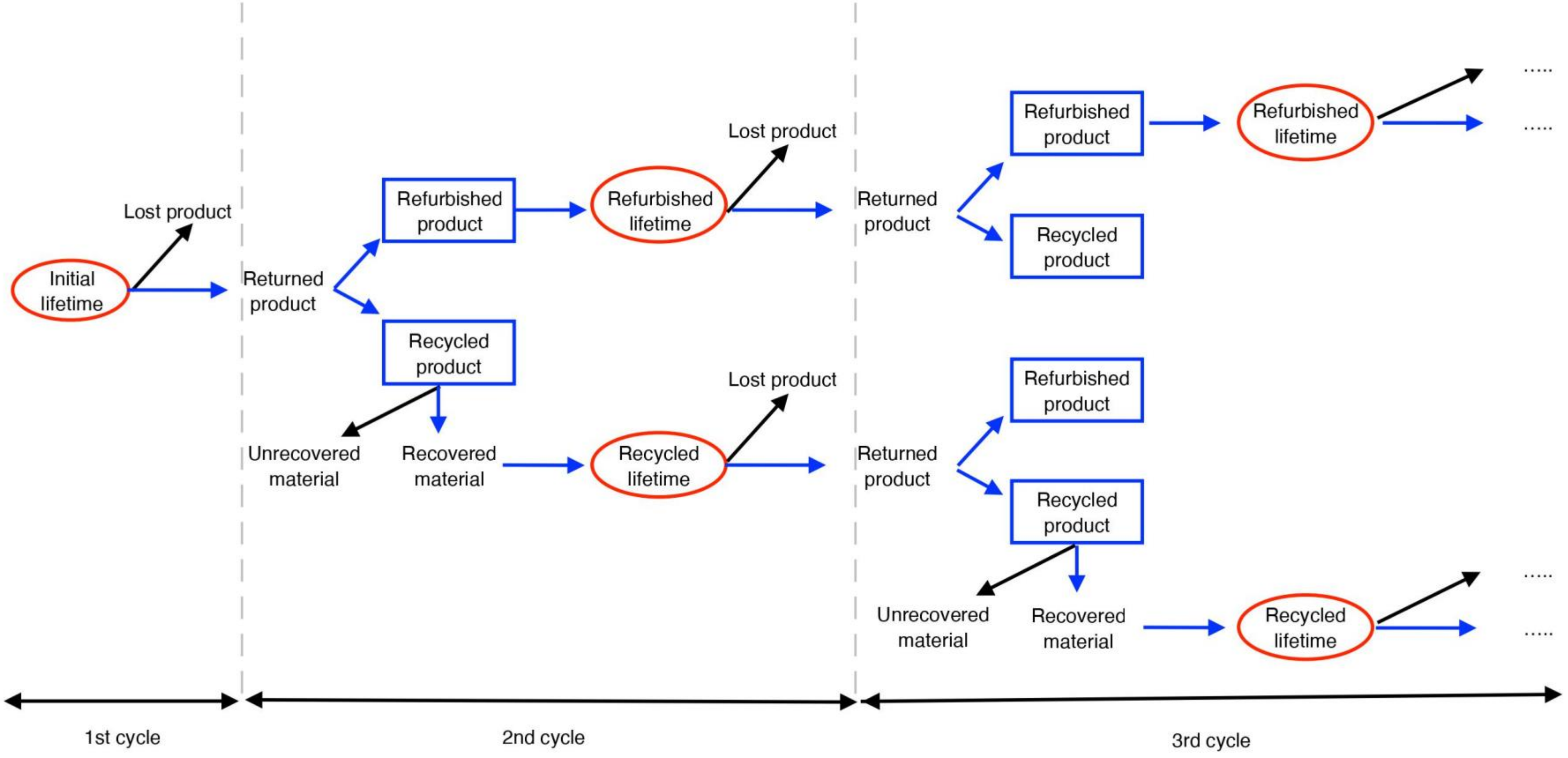


Figure 7: Iterative lifecycles of refurbished and recycled products. (Adapted from Franklin-Johnson et al. (2016)).

In fact, the number of returned products and products selected for recycling and refurbishment will change each cycle, with the number of returned products for refurbishment will decrease each time and the number of returned products for recycle will increase each time because of technological advancement, material exergy obsolescence, and product functional obsolescence. Therefore, to lift the first assumption that Figge et al. (2018) made (as written above), an adjusted generalized equation can be formed:

$$C = 1 + \sum_{i=2}^{n} \left[\prod_{j=1}^{i-1} (a_j b_j + a_j c_j d_j) \right] \qquad (8)$$

with j denotes the ordinal number of the specific cycle. For example, if there is in total 4 cycles that the material can serve, with 1 in virgin product and 3 in retreated products, then we will have material circulation as

$$\begin{aligned} C = 1 &+ (a_1 b_1 + a_1 c_1 d_1) + (a_1 b_1 + a_1 c_1 d_1)(a_2 b_2 + a_2 c_2 d_2) \\ &+ (a_1 b_1 + a_1 c_1 d_1)(a_2 b_2 + a_2 c_2 d_2)(a_3 b_4 + a_3 c_3 d_3) \end{aligned}$$

To examplify equation (8), the same numbers are taken from the study of Figge et al. (2018). Because there are 3 cycles with 2 additional cycles that we can have

$$\begin{aligned} C &= 1 + (0.15 \times 0.65 + 0.15 \times 0.35 \times 0.95) + (0.15 \times 0.65 + 0.15 \times 0.35 \times 0.95)^2 \\ &= 1.16909\ (times) \end{aligned}$$

Comparing between their results and our results, the error is pretty small. Despite the fact that for falsification process, comparison between two methodologies with a number of different trials are needed, yet the results are still persuasive. To improve the reliability with test-retest strategy, more data will be used to compute as examplification for the methodology of this study in section 5.

Two important factors regarding the essence of recycled material are its quality and quantity. There are different viewpoints towards two aspects among the literatures of recycling. On one hand, Nelen et al. (2014) separates the concept of recycling quality and quantity as two distinct prospects. According to their indicators formation, recycling quantity is calculated by the differences of the total weight input of recycling process and total weight of recycled target material; while recycling quality is computed by using the proxy of prices of recycled materials. In spite of the fact that market prices of recycled materials can reflect its quality – or impurity – it still possesses within itself the concept of planned obsolescence, in which the price of virgin materials is always considered as the leader in the market (Chen and Liu, 2014), thus leading to a heavy financial effect in recycling decisions (UNEP, 2013a). Moreover, prices of secondary metals in some cases can overcome the prices of virgin extracted ones (Zeng et al., 2018), which will distort the intention of using price as the proxy for material quality. On the other hand, material quality is addressed by computing exergy lost of materials through consumption, recovering and recycling (Castro et al., 2007), or energy difference from net energy saving of recycling and its material embodied energy (Steinmann et al., 2019). Although these engineering computations will attain correct answers of material quality without including the planned obsolescence effects like the proxy method above, it is quite complicated for computation. **Based on the fact that different methods and targets of recycling will result in differences in recycling ratio of materials (UNEP, 2013a,b), utilizing the primary data from manufacturers and recyclers is the best option to express the factor $(\boldsymbol{d})$ of recycling ratio**. Thus, the thesis addresses recycling ratio as both the embedded quality and quantity of material recycle process.

Additionally, the study contributes one advanced section of material circularity – the discovery of min-max circularity range of material within the technosphere – which Figge et al. (2018) did not address. From equation (7), the minimum circularity value of a material will be 1 (serves only the 1st cycle). To find the maximum value, there must be a constraint with regard to the percentage of recovered materials at the last phase. Based on the model of iterative cycles, if we follow the assumptions, then the percentage of products retained from refurbishment and recycle process is constant after every cycle (v), thus:

$$v = ab + acd$$

There are two ways to calculate the number of potential circulation times. The first method is to utilize the total weighted input amount of material in a number of products and the last insufficient amount to manufacture one product. The calculation of letting the last insufficient value divide to the total input value implies the last retained yet insufficient percentage of material after cycles of waste retreatment. As losing materials due to lost products and unrecoverable waste from recycling process that the factor (v) will get smaller and smaller, depicts the decreasing in contributed circulation of materials. Thus, to find the maximum circulation cycle, we attain the formula:

$$v^n = \frac{last\ insufficient\ amount}{total\ input\ amount} \tag{9}$$

If we define the right side of equation (9) as $r = \frac{last\ insufficient\ amount}{total\ input\ amount}$, we can change it to the logarithm form:

$$n = \frac{\log(r)}{\log(v)} \tag{10}$$

If it is possible to have the access to the bill of materials, then the insufficient amount of a material to make a product can be obtained. However, in the case of rare earth materials, the necessary amount for manufacturing a product is so small that for simplification, we can have the insufficient amount of material as 1 unit and then the factor (r) can be written as:

$$r = \frac{1}{M}$$

with M stands for the total mass input of the material. Then equation (10) can be transformed:

$$n = \frac{-\log(M)}{\log(v)} \tag{11}$$

Advantage of using this approach is that the data for amount of materials input is usually accessible in the supply chain. Corporations and companies can track down data from inventories to know exactly how much of the amount is used each manufacture time. However, the more input is installed into manufacturing process, the longer the cycles will be. Thus, to compare the recycling and refurbishment circularity contribution between two or more cases, a same and finite number of material input should be maintained to hold the reliability of the approach. In case of differences in mass input between scenarios, the result for maximum number of cycles will not be reliable to examine. One more disadvantage of the method is data availability, with which usually restricted within corporations' access. Because of these drawbacks that the second approach is addressed below.

The second method is to employ the minimal percentage of circulated materials before it is seen as totally obsolete. If we call (u) as the percentage at which the last fraction to gain back materials from waste treatment strategies, which is so small that the amount of material can be seen as totally obsolete, then we can change equation (9) into:

$$v^n = u \tag{12}$$

Change equation (12) into logarithm form, we shall have:

$$n = \frac{\log(u)}{\log(v)} \tag{13}$$

The strongpoint with regard to this approach is that it does not take into account the mass weight of input material but the last percentage at which material can be seen as obsolete from the technosphere. As factor (u) is the smallest percentage of circulated material before being obsolete that it also has the form as same as factor (v). We can have:

$$u = a_{min} \times b + a_{min} \times c \times d_{min}$$

with a_{min} is the minimum percentage of collected products and d_{min} is the minimum recycling ratio. Since the recycling rate in this case depends merely on technological advancement that factor (d) will not vary greatly but only is a specific range. Other factors which can influence the recycling ratio, such as legislative and economic limitations (UNEP, 2013b), will put more pressure on factor (a). The percentage of product collection in the EoL treatment (a) stands as the most important factor in material circularity picture, because without returned products, material cannot continue its next cycles as refurbishment products or enter recycling process for other virgin products. Therefore, the value of factor (a) can take the smallest values, depending on the collection ratios of different products. Nonetheless, until now the author still cannot find the source from which data for factor (u) is scrutinized or discovered. However, based on various reports about EoL treatment of electrical products, factor (a) can take the value of the worst waste treatment scenario. Additionally, to follow this approach, decision-makers can take advise from specialists to set their own numbers.

3.3.2. Material longevity metric

Among various circular economy indicators, not so many of them are created to measure product and material lifetime extension (Parchomenko et al., 2019). There are two main metrics mentioned in several reviews (Helander et al., 2019; Moraga et al., 2019; Kristensen and Mosgaard., 2020) that pay major attention to longevity element of the material, which are the MCI of Ellen MacArthur Foundation and CM of Figge et al. (2018). On one hand, MCI utilizes product lifespan of a product, which is compared with the industrial average product lifetime, to form product utility fraction for calculating circularity in the end. The indicator does not point out significant contribution of material circulation on its lifespan, thus acting as a hindrance to indicate lifetime extension within circular economy concept. On the other hand, CM calculates longevity based on the result of material circularity. The more material circulates within the technosphere, the longer material can serve the economy. Although the article of Figge et al. (2018) is taken as the background for this thesis, since material circularity is approached by different aspects that material longevity is also adapted and adjusted. The author names their approach as “material longevity within the product” and ours as “material longevity within the economy”.

3.3.2.1. Material longevity within the product

Longevity of a material is defined as *“the length of time that the resource is used, which can be measured in days, months, years, and so on.”* (Figge et al. 2018). Longevity is rising as one of the critical element within the circular economy concept, yet lack of attention due to the imbalance in waste management and resource recovery topics. To avoid being confused, the study addresses 3 kinds of longevity: (1) product lifetime; (2) material longevity within the product; and (3) material longevity within the economy. The 1st terminology is the lifespan of product itself, in which the temporal calculation ends when the product is disposed. The 2nd terminology is addressed in this sub-section as the length of time that material can travel inside virgin and refurbished products until being recycled. The 3rd terminology is mentioned in the next sub-section as the total lifetime of material from the 1st life cycle, through several times of refurbishment and recycling, until it is obsolete.

Material longevity is seen as how long a material can serve the economy after cycles of waste treatment. Therefore, according to Figge et al. (2018), longevity equations are also constituted from circularity background. To calculate material longevity – or resource lastingness – we also count the lifetime contribution of the virgin phase, refurbished phases, and recycled phases. Thus we can achieve:

$$Longevity = L^A + L^B + L^C \tag{14}$$

with L^A as the lifetime of initial use, L^B as the lifetime of the refurbished product, and L^C as the lifetime of the recycled product. The unit is temporal, such as hours, days, months, or years.

Since refurbishment stimulates material circulation that it also extends material lastingness. If (i) denotes the ordinal cycle after the 1st lifetime, then L_i^B stands for the lifetime of a product at the ith cycle. We can aggregate it to equation (3) and get:

$$L^B = \sum_{i=1}^{n} \left[\left(\prod_{j=1}^{i} a_j b_j \right) L_i^B \right] \tag{15}$$

Longevity throught recycle process is also considered as the last part of the longevity equation. Therefore, according to equation (5), we can have:

$$L^C = \frac{p}{1-p} (L^A + L^B) \tag{16}$$

with the factor (p) keeps the same value from equation (4).

One important assumption in the case of product lifetime is that the lifetime of refurbished products are usually shorter than of the original one. Because of this assumption that Figge et al. (2018) added one factor called (α) (with $\alpha < 100\%$) to equation (15). Holding the idea that *"the lifetime of a product through refurbishment decreases constantly with every step"* (Figge et al., 2018: 301) that

$$L_i^B = \alpha L_{i-1}^B \quad with\ i = 1, \dots, n; \quad and\ \ L_0^B = L^A$$

Hence, we can also achieve as $L_i^B = \alpha^i L^A$.

Conclusively, from equation (6) of material circularity within the product, we can have material longevity in the same scope as:

$$\begin{cases} Longevity = L^A + L^B + L^C \\ L^B = L^A \left[(ab\,\alpha)\left(\dfrac{1 - (ab\alpha)^n}{1 - (ab\alpha)}\right)\right] \\ L^c = L^A \left[\left(\dfrac{p}{1-p}\right)\left(\dfrac{1 - (ab\alpha)^{n+1}}{1 - (ab\alpha)}\right)\right] \end{cases} \tag{17}$$

Applying the calculation of material longevity to the data from Figge et al. (2018), with $L^A = 24\, months$ and factor $\alpha = 50\%$, refurbishing process contributes an additional of 5.12% in lastingness and recycling process extends a surplus of 5.87% in lifetime of gold. (Figge et al., 2018: 303). In total, lifespan of gold was prolonged as:

$$Longevity = 24 + 1.23 + 1.41 = 26.64\, months$$

3.3.2.2. *Material longevity within the economy*

Utilizing the unit of C as material circularity that our calculation for material lastingness takes the temporal unit, such as hours, days, months, years, and so on. The more times material can circulate within the technosphere, the longer it can serve the economy before becoming uncoverable and obsolete. There are several reasons which the study decided to pursue a different approach towards material longevity of Figge et al. (2018). First of all, it is not accurate that product lifespan through refurbishment will be shortened constantly after each cycle. A study of Huang et al. (2020) showed that based on the research about longevity of products collected for recycling process, it turns out that "*the lifespan of products arriving at the recycling plants is generally much longer than that estimated from questionnaire survey on the discarding behavior of consumers*" (Huang et al., 2020: 104700). **Thus even though there can be a factor (α) in the longevity equation, it does not need to increase its influence exponentially through times.** Moreover, refurbishment process can enhance material longevity if the product is well designed. *"Utilization of excess materials–for example, for improvement of unit strength–can enable a reusable unit to endure over a period equal to at least two functional lives"* (Okumura et al., 2003: 3667). Therefore, the action of multiply product lifespan in temporal values to the result of material circularity does not take into account for the actual lifespan of refurbished products, especially after several times of refurbishment (since the factor (α) at that time will generate geometrically).

Due to the fact that refurbished products have shorter lifespan than original and recycled products that **the range of lifespan for an amount of material to flow will obtain two absolute values, minimum total lifespan and maximum total lifespan**. The reason for this longevity interval lies in the fact that different customers have different consumption behaviours, which causes variation in product lifetime extension. Furthermore, when a number of products are sold to the market, it is nearly impossible to trace all lifetime of products. Thus, having one absolute number like the approach of Figge et al. (2018) is unrealistic.

There are several factors that constrain the expansion of the min-max range. On one hand, maximum product lifetime will be constrained by consumption trend, product prices and functional value, and technological obsolescence. Different kinds of planned obsolescence can orientate consumption trend of dumping old products and changing to new ones, such as "Function planned obsolescence" – by forcing the customers to update more programs or creating new functions in new products which the old ones cannot have, "Quality planned obsolescence" – by decreasing durability of the product, and "Desirability planned obsolescence" – by creating new and unnecessary desires. Mass production and technological advancement can elevate the cost per functional unit, which also constrain the maximum lifespan of a product. On the other hand, minimum product lifetime will be limited by material degeneration, as if the products are refurbished by several times, it is more likely that the material will enter the recycle process and start a new recycled cycle than continue its flow within the old products. **Therefore, the minimum value of material longevity can be seen as the result from refurbishment process, while maximum value of material longevity can be considered as the outcome of recycle process.**

The value of material longevity is minimized by consumption behaviour and functional value of refurbishment products, thus we can have:

$$L^B = \alpha L^A$$

with L^A denotes material longevity of the 1st cycle, and L^B denotes material longevity of the refurbished product. Besides, the value of material longevity is sustained by recycling process, which leads to:

$$L^C = L^A$$

as L^C denotes material longevity of the recycled product. Therefore, we can have material longevity with its total range as:

$$Longevity = L = [L^A + (C - 1)(\alpha L^A); L^A + (C - 1)(L^A)] \tag{18}$$

The reason that material circularity value has to minus 1 is due to the fact that product lifetime of the initial phase (1st cycle) has been counted. If the formula utilizes C but not $(C - 1)$, then longevity of the 1st cycle will be double counted. The first phase of $L^A + (C - 1)(\alpha L^A)$ stands for the minimum material lifetime when circulation is taken into account, and the second phase of $L^A + (C - 1)(L^A)$ stands for the maximum material lifetime when circularity is aggregated. The accute difference between the minimum value and maximum value is factor (α). The larger the factor (α) can be, the bigger the range between min-max values. Thus, to increase product lifetime extension, refurbished products need to be designed to have equal functional values comparing to new ones. Once values are equal between two kinds of products, we will have positive change from consumption behaviours, which leads to higher rates of material circulation and lastingness.

Applying the data from Figge et al. (2018) with $\alpha = 0.5$ into this approach, we can have:

$$[24 + (0.1676 \times 0.5 \times 24); 24 + (0{,}1676 \times 24)] = [26.0112; 28.0224]\ (months)$$

The result can be interpreted as thanks to refurbishment and recycle treatments that material longevity was extended to the range of about 26 months to 28 months, comparing to the original lifetime as 24 months. The answer from Figge et al. (2018) as 26.64 (months) also falls into the material longevity interval, proving the reliability of the Material Circularity Metrics Chain.

3.3.3. Material retainment outcome

Thanks to EoL treatment that material can be partly recovered and re-enter the technological loop. Following the flow of benefits from material circulation, other relevant metrics are added to illustrate the importance of circularity, thus encouraging policy-makers to pay more attention to the circular economy concept. Material circularity contributes not only to product lifetime extension but also to emission curtailment and energy reduction due to using less extracted virgin materials for production. Since only few circular economy indicators addressed the social impact of sustainable development framework (Geissdoerfer, 2017; Parchomenko et al., 2019) that the author decided to investigate in one tiny yet pressing social aspect of the mining industry: child labour prevention problem. Among several reviews about circular economy metrics, only one scrutinized the element of child labour in material supply chain (Iacovidou et al., 2017).

3.3.3.1. Emission retainment metric

Greenhouse emission, global warming, or the anthropogenic distortion of the environment is no more the debate but has become the fact. *"Altogether, metal production today represents about 8 per cent of the total global energy consumption, and a similar percentage of fossil-fuel-related* CO_2 *emissions"* (UNEP, 2013a: 40). Thus, material recirculation within the economy plays an important role in emission reduction. Emission of material can be calculated based on its life cycle. For the minerals to be extracted and purified, huge effort is put into the process, thus making the process as energy intensive and creating a heavy burden of emission to the environment (UNEP, 2013a). Materials then go through product manufacture phase and consumption phase, which also releases emission. Eventually, after spending all of their utility in the finished product, to prevent precious and useful materials to enter incineration and landfill, recycling process is needed. Emission is unavoidable in this stage due to the Second Law of Thermodynamics. Thus, emission present through all the phases of a full material cycle.

Based on the iterative cycles of refurbishment and recycle above, a formula to calculate retained emission of material can be built upon. As the first cycle of the product, total emission is computed as the sum of emission from material extraction, product manufacture, and consumption phases. We can have:

$$em_1 = em_{extraction} + em_{production} + em_{consumption} \tag{19}$$

with em_1 denotes the emission of the first cycle, $em_{extraction}$ as the emission of material extraction and purification process, $em_{production}$ as the emission from product manufacturing and transporting processes, and $em_{consumption}$ as the emission of the consumption process.

Emission of the refurbishment cycle consumes much less energy, since the whole product is refurbished quickly and then resold to reuse. Emission from material extraction and product manufacturing phases are saved, thus devoting in emission reduction for the environment. We can have the emission of the refurbished product in one cycle as:

$$em_{RF} = em_{consumption} \tag{20}$$

Therefore, the retained or saved emission from refurbishment strategy of one cycle is in fact the $em_{production}$ and $em_{extraction}$, which leads to:

$$em_1 - em_{RF} = em_{extraction} + em_{production} = EM_{RF} \tag{21}$$

with EM_{RF} denotes the retained (or saved) emission of the refurbishment strategy of one cycle.

Equation (21) only provides the information about how much emission can be retained from the refurbishment strategy of 1 cycle, which has not included the factor of circularity. Thanks to circulation that refurbishment strategy can occur several times, which continuously increases the final value of total of EM_{RF} until the material goes obsolete. By adding factor of material circularity to get the most of retained emission, we will attain:

$$(n-1) \times EM_{RF}$$

The reason of not using $(C-1)$ just as in the case of material longevity but $(n-1)$ lies in the fact that after each cycle, the amount of origin metal will decrease due to losing metal from recycling. Thus, material longevity (L) measures the expanded lifetime of the amount of material as if in the following cycles the amount of origin metal is still the same. That is why $C < n$. However, in the case of emission, the emission is retained after each time the product itself is refurbished or recycled, thus the number of cycles of product (n) is used here.

Emission of recycling process differs much from emission of refurbishing process, due to the excess energy required for material recycle and the imperfect recycling ratio of all materials (UNEP, 2013a). There are several limitations that suppress the excellence of recycling ratio. Firstly, due to customers' demand and market trends that technologies within products are integrated complicatedly, thus leading to difficulties in recycling steps such as sorting, separating, and other metallurgy processes. Secondly, policies regarding WEEE treatment are not yet well developed and different across nations and regions, increasing the complexity of E-waste collection. Thirdly, different metals possess different characteristics yet they are intertwined with each other in small electronic products, thus limiting the recycling ratio. However, the energy needed for material recycling usually is much lower than the one required for material mining and refining, since scrap from shredded metals require much less energy to convert back into high-qualified ones. The emission of the recycled product in one cycle can be computed as:

$$em_{RC} = d \times em_{RC\ step} + (1-d) \times em_{extraction} + em_{production} + \ em_{consumption} \qquad (22)$$

which em_{RC} is the emission of the recycled product in one cycle, $em_{RC\ step}$ is the emission of material recycling steps, such as cleaning, sorting, shredding, smelting, etc., and $(1 - d) \times em_{extraction}$ is the emission of the added amount of material for purification and producing a new product (since the recycling ratio is hardly ever equal to 100%). Factor (d) is the recycling ratio, and $(1-d)$ is the left fraction that new material have to enter for product manufacture.

Although (em_{RC}) and (em_1) has 1 common part as $(em_{production} + \ em_{consumption})$, the difference of the term $(em_{extraction})$ and $(d \times em_{RC\ step} + (1-d) \times em_{extraction})$ indicates the dissimilarity of emission between virgin and recycled product. To illustrate the difference, we can have the retained emission of the recycle strategy of one cycle as:

$$\begin{aligned} EM_{RC} &= em_1 - em_{RC} \\ &= em_{extraction} - [d \times em_{RC\,step} + (1-d) \times em_{extraction}] \end{aligned} \tag{23}$$

If $EM_{RC} < 0$ then the emission of recycling strategy has surpassed the emission of producing virgin material, which leads to inefficiency and uneconomical outcome of the recycle approach. In contrast, if $EM_{RC} > 0$ then the emission of producing virgin material is still larger than of the recycling option, which encourages more material circulation within the technosphere. According to UNEP (2013a: 83), *"carbon emissions from recycling are substantially inferior to those from mining, which are likely to increase due to the rising use of lower-grade ores"*. **Therefore, most of the time EM_{RC} takes a positive value**.

As the factor of recycling ratio has been embedded in EM_{RC} that when material circulation factor is combined with the retained emission of the recycle strategy, we can achieve:

$$(n-1) \times EM_{RC}$$

To compute the total emission retainment of both refurbishment and recycle processes throughout iterative cycles, we can have:

$$EM_{RF+RC} = [b(n-1)EM_{RF} + c(n-1)EM_{RC}] = [(n-1)(bEM_{RF} + cEM_{RC})] \tag{24}$$

The input of factor (b) and (c) depicts the weighted percentage of refurbished and recycled products, which in the end will impact the total average retained emission. Comparing between the contribution of retained emission of both strategies, from equation (21) and (23) we can see the difference of EM_{RF} and EM_{RC} is:

$$EM_{RF} - EM_{RC} = em_{production} + [d \times em_{RC\,step} + (1-d) \times em_{extraction}]$$

On one hand, from some works about life cycle analysis among electronic products that usually emission from production (including manufacturing and transportation) is the highest within the supply chain (Olivetti et al., 2013; Andersen et al., 2014; Foelster et al., 2016). One the other hand, as emission from recycling steps is quite small comparing to material extraction of product manufacture that

$$em_{RC\ step} < em_{extraction}$$

Due to the fact that recycling strategies and technologies are putting much more effort (UNEP, 2013a), especially with the concept of "urban mining" (Arora et al., 2017; Boxall et al., 2018) that the factor (d) will rise higher in the future, therefore leading to the continuous decrease of $(1-d)$. Following the trend, share of emission of added virgin material in the recycling process will decrease vastly, which eventually minimizes the whole phrase of $[d \times em_{RC\ step} + (1-d) \times em_{extractiom}]$.

As the phrase of $\{em_{production} + [d \times em_{RC\ step} + (1-d) \times em_{extraction}]\}$ will always larger than zero that conclusively, **the retained emission of refurbishment strategy is always larger than the saved emission of recycling strategy.**

3.3.3.2. Energy retainment metric

If emission is the byproduct from material flow within the economy, then energy is the input for anthropogenic cycling of metals. In all the supply chain, energy is needed for material extraction and purification, product manufacture, commodity transportation, device operation and EoL waste treament. Thus, the circular economy concept with material circularity will enhance metal flows within the anthropogenic sphere, limiting material leakage and loss thanks to the recycling process. According to the report of UNEP about environmental risks of metal cycles, recycling can save from 55 upto 98% of energy (UNEP, 2013b). Therefore, as a matter of fact, the more times material can circulate within the technosphere, the more energy can be retained.

With the iterative cycles of refurbishment and recycle, the formula for retained energy of material can also be found. In the first cycle, the energy required to for the whole life cycle of the product (in case product is returned and not be treated as waste in the EoL stage) is the sum of energy for material extraction, product manufacture, and consumption phases. Then we can have:

$$en_1 = en_{extraction} + en_{production} + en_{consumption} \qquad (25)$$

with en_1 denotes the energy for the first cycle, $en_{extraction}$ as the energy to extract and purify metal, $en_{production}$ as the energy to manufacture and transport product, and $en_{consumption}$ as the energy for the consumption phase. As this is the equation for the necessary energy for the first virgin product, no retained energy can be achieved in this phase.

As same as the methodology for retained emission, energy can also be saved in the refurbishment and recycle processes. This part adapts the developed equations for retained emission above.

As emission decreases vastly in the refurbishment process decreases , so does the energy it requires. Energy for material extraction and product manufacturing phases are saved, thus increasing energy conservation. Since the only source of energy is needed for consumption phase of the product that we can have the energy for the refurbished product in one cycle as:

$$en_{RF} = en_{consumption} \tag{26}$$

Thus, the retained energy from refurbishment strategy of one cycle is in fact the $en_{production}$ and $en_{extraction}$, which leads to:

$$en_1 - en_{RF} = en_{extraction} + en_{production} = EN_{RF} \tag{27}$$

with EN_{RF} denotes the retained (or saved) energy for the refurbishment strategy of one cycle.

By adding factor of material circularity to get the most of retained energy, we will attain:

$$(n-1) \times EN_{RF}$$

The energy for the recycled product in one cycle can be computed as:

$$en_{RC} = d \times en_{RC\,step} + (1-d) \times en_{extraction} + en_{production} + en_{consumption} \tag{28}$$

which en_{RC} is the energy for the recycled product in one cycle, $en_{RC\,step}$ is the energy for recycle material steps, and $(1-d) \times en_{extraction}$ is the needed energy for the added amount of material for purification and producing a new product (since the recycling ratio is hardly ever equal to 100%). Factor (d) is still the recycling ratio, and $(1-d)$ denotes for the part of new material which is put to replace the lost from recycling process.

We also can attain the formula for the retained energy of the recycle strategy in one cycle as:

$$\begin{aligned} EN_{RC} &= en_1 - en_{RC} \\ &= en_{extraction} - [d \times en_{RC\,step} + (1-d) \times en_{extraction}] \end{aligned} \tag{29}$$

The result of equation (29) can takes two value. If $EN_{RC} < 0$ then the energy for material recycling is bigger than the energy to extract and purify new material, thus making the recycle strategy as impossible. Contradictorily, if $EN_{RC} > 0$ then the energy for producing virgin material is still larger than of the recycling option, which encourages more material circulation within the technosphere. **Mostly EN_{RC} takes a positive value** because according to the report of UNEP:

> *"The production of metal from scrap material, or secondary production, generally requires much less energy than for primary production, as many fewer steps are involved… As the scrap material portion is already in metallic form, much less energy is needed to reduce the metal. All of the energy used in mining, milling, concentrating, and transporting ore to a smelter is also avoided when recycling metals."* (UNEP, 2013b: 84)

Then we can achieve:

$$(n-1) \times EN_{RC}$$

Adapting from equation (24), we can get:

$$EN_{RF+RC} = [b(n-1)EN_{RF} + c(n-1)EN_{RC}] = [(n-1)(bEN_{RF} + cEN_{RC})] \tag{30}$$

Similar to the methodology of retained emission that **the saved energy of refurbishment strategy is always larger than the retained energy of recycling strategy.**

3.3.3.3. Child labour prevention metric

The reason why child labour is not widely noticed by many reviews of circular economy indicators takes it root from how the metrics are developed. In a common viewpoint, circular economy indicators are developed mainly by LCA and MFA methodologies, which only focus in the environmental and economical aspects of production and consumption, thus neglecting the presence of social prospect. Child labour is mentioned in a literature review about the Social Life Cycle Assessment, one of the refined edition of LCA (Wu et al., 2014). To balance the influence of material circularity and longevity on three sustainable development pillars, the study addresses child labour issue as the representative factor for the social pillar. Although there are several other social factors such as job creation or social security which are benefited from initiatives of circular economy, child labour is the most bitter and poignant consequence of planned obsolescence and consumerism. As the age of IoT has come, the mining industry has to bear heavier burden of increment in material demand (UNEP, 2013a), which can cause severe impact on children in under-developed and developing countries in South America, Asia, and Africa. Thus, the more circularity a material can achieve, the fewer children are to be exploited for the mining industry.

Definition of child labour varies with gradually narrowing scopes. Based on the latest report about child labour of the International Labour Organization (ILO), there are several scales of child labour, starting with *"children in employement"* as any form of work that children carry out, *"children in child labour"* with the exclusion of permitted light work and non-harzadous work, and *"children in the worst form of child labour"* as those who have to suffer slavery, forced labour, child prostitution, or have to work in the hazardous condition (ILO, 2017a). Although children working within mining and quarrying industries are seen as the smallest in total share, they have the most exposability to hazardous working conditions (Faber et al., 2017). The study concentrates on how material circularity can reduce and then avoid children presence in the mining industry.

In spite of not being mentioned frequently as a distressing problem in material supply chain, several efforts have been made to draw more attention to the working conditions of children within mining and quarrying sectors (ILO, 2006; Amnesty International, 2016; Frankel, 2016; Kara, 2018; Kelly, 2019). According to various mentioned investigations, child labour issue surrounds often with the exponentially rising in demand for advanced electronic and electrical equipment such as smartphone, laptop, tablet, and especially in the demand of electric vehicle along with the special requirement of lithium-ion battery. Gold, silver, copper, with a full range of rare earth materials are being extracted as much as possible because of the unstoppable demand of virgin materials, even when recycling has been accounted for (UNEP, 2013a). The demand is so gigantic that there has been a shift from mining high-grade ores to extracting low-grade ores, which even put workers in the worse situations because of longer working time per unit mass of extracted material.

Until now there is no public report or study which addresses the relationship of material circularity, or at least dematerialization, and the hours of child labour in the mining industry. Hence the thesis contributes to the literature of circular economy with a metric which can engage material circulation to child labour reduction and avoidance. Since there is not much available data in micro scale that the formula needs a top-down approach.

Data for child labour is reported in different ways. The ILO reported child labour with population features such as sex, age, and originated regions (ILO, 2017a). Child labour regarding to the participation in economic sectors are mentioned, yet there is no specific number relating to percentage or amount of children working in the mining and quarrying sector or in Artisanal and Small-scale Mining (ASM). Since the number of children in the mining quarrying industry is small comparing to the total figures that it is usually combined with other sectors under the name “others” or “hazardous work” (UCW, 2016). The number of children who are categorized as working in hazardous work is considered as working in mining and quarrying, construction, and manufacturing sectors. Percentage of children working in material extraction supply chain is reported in other works, yet they only have the meso level as country perspective, such as about cobalt mining in Democratic Republic of Congo (Faber et al., 2017), Tin Mining in Indonesia (ILO, 2014), etc. One research about illegal gold mining in the Latin America did address specific numbers of children of each country (The Global Initiative, 2016).

To see the impact of material circulation on number of child labour hours necessary to mine a unit mass of that material, there is a need of gathering and computing data from a wider yet deeper perspective. Fortunately, the U.S. Department of Labor did publish a list of goods which are produced by child labour and forced labour (2018a), with a clear and specific references (2018b). From here, a top-down approach can be carried out.

On one hand, the number of child labour hours per unit mass of material can be computed as following. Firstly, as one kind of material can be supplied by several nations, a list of countries in which children are employed to work for the supply chain of a specific material need to be conducted. As data varies in different forms between countries, unified units are necessary for easy calculation. To find number of child labour hours per unit mass of material, we can have

$$H = \frac{T}{P} \tag{31}$$

with H denotes the number of child labour working hours needed to extract 1 unit mass of material, T denotes the total working hours of total children in 1 year, and P denotes the total production by children in 1 year.

T can be computed by the fact that:

$$T = number\ of\ children\ \times\ average\ working\ hours$$

as "$number\ of\ children$" is the total number of children in each country which uses child labor to extract and export goods, and "$average\ working\ hours$" is the total average hours one child need to work in 1 year of that country. For all the countries in the list, we will have

$$T = \sum_{first\ nation}^{total\ nation} (number\ of\ children\ \times\ average\ working\ hours)$$

As the data for the absolute number of children is not available in reports of all the countries in the list, we can attain:

$$number\ of\ children = \%\ of\ child\ labour\ \times\ total\ ASM\ labour$$

in which "$\% \ of\ child\ labour$" is the percentage of child labour in one country for mining a particular material in all mining labour, and "$total\ ASM\ labour$" is the total number of labour in the mining industry under ASM.

P can be calculated as:

$$P = \% \ of\ child\ labour\ \times\ total\ ASM\ production$$

with "$total\ ASM\ production$" is the total amount of material production in one country by ASM. If there is more than 1 country which utilizes child labour to extract the material, then

$$P = \sum_{first\ nation}^{total\ nation} (\% \ of\ child\ labour\ \times\ total\ ASM\ production)$$

Therefore, from equation (25) we can achieve:

$$H = \frac{\sum_{first\ nation}^{total\ nation} (\% \ of\ child\ labour\ \times\ total\ ASM\ labour\ \times\ average\ working\ hours)}{\sum_{first\ nation}^{total\ nation} (\% \ of\ child\ labour\ \times\ total\ ASM\ production)} \tag{32}$$

On the other hand, for combining the factor of material circulation to the child labour picture, we can gain:

$$CL = (C - 1) \times m \times H \tag{33}$$

with CL is the retained/ saved number of child labour working hours thanks to product refurbishment and material recycling and m is the weight of material in one product. As refurbishment and recycle process occurs, the mass of materials can be maintained, thus gradually reduces working hours of children in developing and under-developed countries.

Within the scope of this thesis, several equations have shed light to the research questions in the introduction part. To answer question (a) of measuring material circularity, equation (7) and (8) have been developed. Question (c) about how many times material can flow within the technosphere has been addressed by the elaboration of maximum value for metal cycles by equation (10) and (11). Material longevity is

mentioned by equation (18), thus answering to question (b) and (d) of measuring material lifetime expansion. Thanks to the aggregation of refurbishment and recycle strategies that retained emission is revealed by equation (24), thus question (e) is answered; and retained energy is disclosed by equation (30), hence question (f) is resolved. Lastly reduced child labour hour per unit mass of circulated material has been clarified by equation (33), therefore bringing the solution for question (g).

4. DATA EXEMPLIFICATION AND DISCUSSION

Although research questions have been addressed in detail by equations development, exemplification is still indispensable for better illustration about the positive effect of material circularity to its lifetime expansion, retained energy, emission, and avoided child labour working hours. The case of smartphone has been selected as an example due to the availability of data, the embedding value and complication of numerous metals, the rising demand as an indispensable individual device, and the symbol of applying technological advancement in daily social life.

4.1. Data collection

The rise of smartphone took root from the 1990s yet until the 2000s that the device started to flourish as a crucial component of everyone's life (Andrew, 2018). From the launch of the first Iphone in 2007 by Apple, the design of a mobile phone has transformed from the basic phone with only calling and texting to the feature phone with more integrated features, and then the smartphone with higher technologies. When the design changed, the sales also transformed. Based on the data on STATISTA, sales of smartphone worldwide has been 10-folded from 2007 to 2014 (O'Dea, 2020). According to Eurostat, from 2013 each European is possessing more than 1 phone due to the increasing number of mobile subscriptions (Eurostat, 2016). Along with smartphone development are its environmental problems. E-waste from smartphone has been accumulated in landfill or exported to low income and under-developed countries although the waste are still in rich of value (ITU, 2017). Because of various types of planned obsolescence that the expected lifetime of a phone has been decreasing 2 times, from 48 months with a basic phone, to 36 months with a feature phone, and 25 months with a smartphone (Güvendik, 2014). Moreover, an average smartphone contains more than 40 kinds of metals such as gold, silver, aluminium, copper, tin, cobalt, tungsten, indium, palladium, and so on (UNEP, 2013a). The extraction and purification processes of the above mentioned metals relate to various indices of ecotoxicity, human toxicity, carbon emission, water wasted, etc. (UNEP, 2013b). Additionally, there are materials are extracted with ethnic and domestic conflicts such as gold, tantalum, tungsten (ILO, 2017b) and child labour such as copper, cobalt, gold, silver, mica, tantalum, tungsten (U.S. Department of Labor, 2018a).

Due to the immense influence of smartphone to environment and society that circular economy has been adopted to diminish the negative effects. Apple, Fairphone, and other mobile phone corporations have been trying to increase the evironmental friendliness of the supply chains by using renewable energy for manufacture, removing toxic elements in product's components, tracking down carbon, water, and fiber footprints of the supply chain, increasing the durability of products, and so on (Apple, 2019; Fairphone, 2020). Based on the available data from several researches about LCA of various smartphone models, about smartphone EoL consumption behaviours, and about reports of metals' supply chains that the thesis decided to take a general smartphone as the example for calculation of material circularity, longevity, and the retained values.

4.1.1. Data of material circularity

Different kinds of data are required to compute material circularity. Figure 8 illustrates how many elements are found in a general smartphone. According to UNEP,

> *"a mobile phone can contain more than 40 elements including base metals such as copper and tin, special metals such as cobalt, indium and antimony, and precious and platinum-group metals including silver, gold, palladium, tungsten and yttrium"* (UNEP, 2013a: 2).

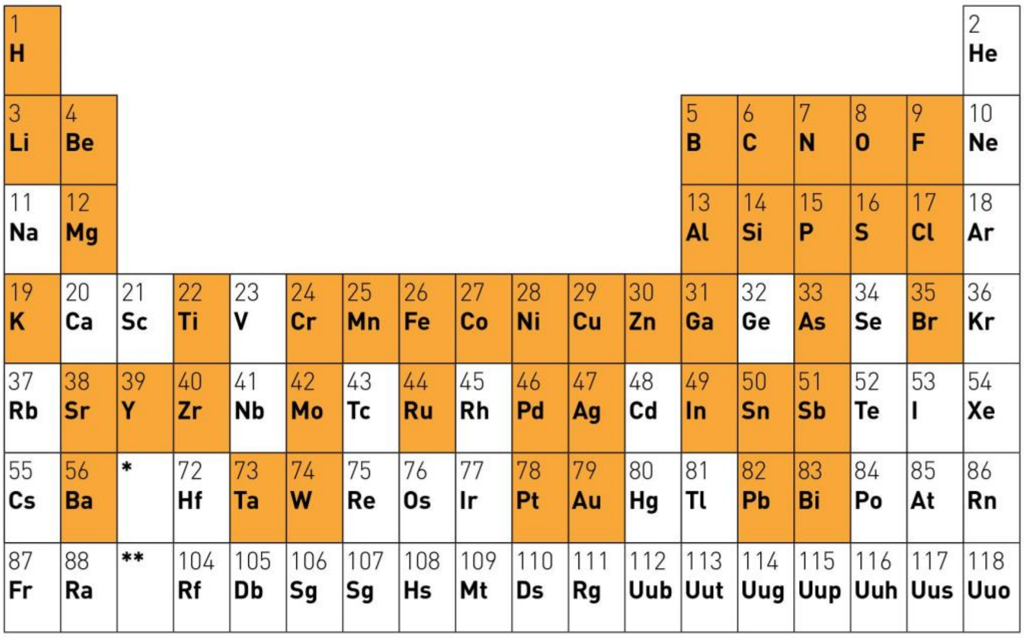


Figure 8: Materials in a mobile phone (UNEP, 2013a: 221)

From the experiment of measuring recyclability of a Fairphone 2, 20 important metals (out of 46) were reported, proving the potential value of E-waste from smartphone (Reuter et al., 2018). Because of data availability and unification with the report about metals of UNEP (2013b) that the thesis has chosen 9 critical metals as the example for theoretical formulas in 2 groups:

(1) Bulk metals: Aluminium (Al), Copper (Cu), Iron (Fe), Nickel (Ni), Tin (Sn); and

(2) Rare and precious metals: Silver (Ag), Gold (Au), Cobalt (Co), Tungsten (W).

The first group is selected due to their vast appliances in not only smartphone but other high-tech devices; whereas the second group is chosen due to their preciousness and their connection to wasted emission, energy, social conflict, and child labour.

While some studies measured the pure ratio of returned phones in total, other studies reported the percentage of collected phones for recycling, repairing, or refurbishing, thus varying the numbers for factor $(a), (b)$ and (c). Moreover, there seems no fixed number of percentage for the three factors due to the lack of waste treatment legislations in many countries (ITU, 2017). Thus, after reviewing the figures from various sources, two scenarios are depicted to compare the magnitude of differences in results that material circulation can bring.

Regard to factor (a), there are several studies considering the percentage of collected or returned phone after serving the first cycle. As a matter of fact, the reason factor (a) is seen as the most important element in the whole E-waste treatment and urban mining is because *"the key to success is to invest in effective collection of the phones"* (Martela, 2019: 29). Franklin-Johnson et al. (2016) used the reported collection ratio of smartphone from Ellen MacArthur Foundation of 15% (EMF, 2017b). Another study about EoL treatment of smartphone in Germany concluded with the percentage of collection is only 5% (Gurita et al., 2018). A survey was conducted in Finland about the consumption behaviours of students towards smartphone EoL treatment showed the percentage of 40% of participants returned the phones for recycling or refurbishment (Martela, 2019). The reason why the percentage of returned phones is still low lies at the fact that users keep the phones at home for data backing-up situations or because they do not know how or where to return the used phones, or they even did not think of recycling them or knew about the possibility of 2nd life cycle (European Commission, 2018b). Several other studies have estimated that more than 120 million phones are hibernating at home in Germany (Bitkom, 2018), more than 3 million phones in Belgium (Green Alliance, 2015), and more than 100 million phones in France (Blandin, 2016). However, based on a thesis about material flow of smartphone in the Netherlands, the collection ratio lies between 30 to 50% from 2008 to 2014 (Uyttenbroek, 2017). A study of The European Economic and Social Committee (EESC, 2019) about the effect of appropriate smartphone EoL treatment gave out three scenarios, with the worst case as the practical case reflecting the lowest percentage of both returned and recycled phones is 22% and the ideal case reflecting the best percentage of both treatments is 95%. Because of variance and non-unification of data that two scenarios are sketched to represent the practical and ideal scenarios of material circularity. Follow the work of EESC, practical smartphone collection ratio is 22% and ideal smartphone collection ratio is 95%. Additionally, to calculate the maximum circulation time of metals, factor (a_{min}) is considered to be 1% as if only 1% of the phone is collected after usage.

Regard to factor (b), percentage of refurbished phones is estimated in various articles. Franklin-Johnson et al. used the ratio of 65% from the study of Geyer and Blass (2010) for the percentage of collected phones entering refurbishment process (2016). Variation of factor (b) depends on the consumption behaviours and market trends of the industry. Although more than 50% of surveyed participants are willing to purchase or use the refurbished product if the conditions are guaranteed (Mugge et al., 2017), if the guarantee is not provided then more than 58% from the research of EESC chose to acquire a brand new phone (EESC, 2019). In fact, only more than 8% has purchased a secondary phones, and the main reason to buy a second-hand phones lies in the low price of the refurbished product (EESC, 2019). The research of Uyttenbroek (2017) found out that in the Netherland, after being dumped as WEEE, mostly the products are not reused but sent immediately to recycling. EESC report provided two extreme scenarios with the lowest refurbishment rate of phones in the EoL stage is 10% and the highest refurbishment rate in the EoL stage is 30%. If the number is fixed to fit this thesis, then the factor (b) for the worst scenario is 45% $\left(\frac{10}{10+12} \times 100 \approx 45\%\right)$ and for the best scenario is 32% $\left(\frac{30}{30+65} \times 100 \approx 32\%\right)$.

Regard to factor (c), more data are available due to the larger attention in recycling process within the waste treatment industry. Franklin-Johnson et al. (2016) chose the percentage of 35% from the same source, while the EMF cited the number of only 20% of E-waste were collected and recycled in 2016 (EMF, 2017b). In 2017, it was estimated that in Finland there is only 10% of phones were put into recycling process (Martela, 2019), and after the survey 15% of the participants recycled their phone (Martela, 2019). While the recycling rate of phones in the Netherland in 2017 was estimated as 13% (Uyttenbroek, 2017), EESC gave out the practical recycling rate in the EoL stage is 12% and the ideal rate is 65%. Because of the assumption that 100% of returned phones either enter refurbishment or recycling process that $b + c = 1$. Therefore, after converting the numbers to fit factor (c), the worst scenario has the percentage of phones entering recycle process as 55%, while the best scenario possesses the rate of 68%.

Regard to factor (d) about the recycling ratio of a specific material, variation of data lies in the reasons and methodologies of recycling. According to UNEP,

"there is more than one recycling rate for metals in a product. Depending on whether economics, processing technology, etc., are the main motivation for recycling, the recycling rates will be different. It is thus obvious that these rates reflect, at most, a statistical-distribution range." (UNEP, 2013a: 51).

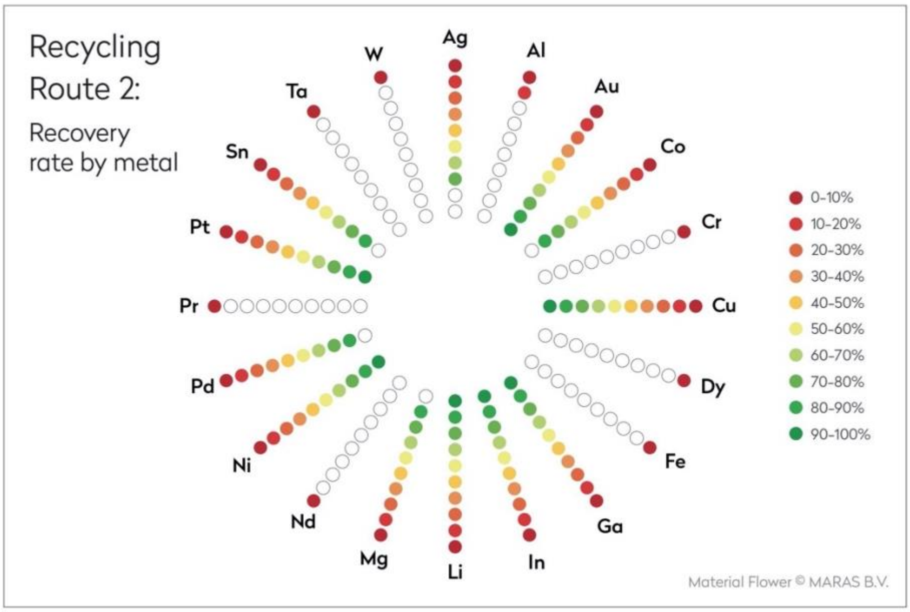


Figure 9: Materials Flower of the Fairphone 2 for Recycling Route 2 (Reuter et al., 2018)

Thus, difference in prioritization of energy, emission, and materials property leads to divergence in metal recycling rate. Another report of UNEP did address several EoL recycling ratios from multiple sources (2013c). However, the data from this source does not process full applicability since it only reflects the data of metals without putting them into the complex context of complicated product designs. Hence

> *"these recycling-rate definitions exclude non-linear physical interactions in the complete recycling chain and therefore have a limited theoretical basis and little predictive value"* (UNEP, 2013a: 47).

The closest data about recycling rates of metals of a phone were studied in the research of using Material Recycling Index (MRI) in finding the best recycle scenario for the Fairphone 2 (Reuter et al., 2018). After experimenting, the second recycling route was chosen because it recovers not only the most variety of materials but also the total weight of metals from a used smartphone. Comparing between the scenarios, Reuter et al. insisted that *"different recycling routes can result in very different recovery rates for specific materials"* (2018: 76). Therefore, the result is chosen for this specific case of smartphone is computed in Table 1; yet in other cases with different prioritization relating to recycling methodology will lead to different results.

Figure 9 shows the result of recycling ratio of 20 metals after being dismantling and smelting. From Fig. 9, the percentages of recycling ratios of 9 metals have been calculated to calculate the material circularity of 9 materials in 2 scenarios.

Table 1: Recycling ratios of 9 selected metals

Metal	**Recycling ratio range**	**Average weighted percentage ($\boldsymbol{d}$)**
Ag (Silver)	70% – 80%	**75%**
Al (Aluminium)	10% – 20%	**15%**
Au (Gold)	90% – 100%	**95%**
Co (Cobalt)	80% – 90%	**85%**
Cu (Copper)	90% – 100%	**95%**
Fe (Iron)	0% – 10%	**5%**
Ni (Nickel)	90% – 100%	**95%**
Sn (Tin)	80% – 90%	**85%**
W (Tungsten)	0% – 10%	**5%**

4.1.2. Data of material longevity

Product lifetime of a smartphone has been measured by several studies. Franklin-Johnson et al. took the number of 24 months (2016), while the manufacturers of various smartphone models – such as Iphone, HTC, Sony, Nokia, Fairphone – ensured in their product public reports that the phone can last for 3 years or 36 months (Apple, 2013a,b, 2014; Suckling and Lee, 2015; Ercan et al., 2016). Due to technological advancement or in another way of speaking is technological obsolescence that lifetime of phone in the western world is considered as 18 months (Franke et al., 2006). The research in Finland shows that average lifetime of a smartphone from students' consumption behaviours is 22 months (Martela, 2019). The case of Fairphone is more interesting since the phone was designed with modular-component replacement. Therefore, the lifetime of a Fairphone can be from 2 years to 6 years in total (Güvendik, 2014). A research about mobile phone lifetime in Czech Republic stated the usage lifetime is 3.63 years (Polák and Drápalová, 2012) and the total presence time of the phone in the market including storage time before disposal is 7.99 years. However, since other reports did not research about the whole lifetime including storage time but only the temporal length for product utility, and also because material lifetime is merely considered when the materials serve their utility that average usage lifetime of the phone is only taken into account. From the two scenarios of EESC, the thesis also employs two different lifetimes for the factor (L^A): the practical and current average lifetime of smartphone is 21.6 months and the ideal lifetime extends upto 45.6 months (EESC, 2019).

Table 2: Different factors' values between two scenarios

Factor	**Practical scenario**	**Ideal scenario**
(a)	22%	95%
(a_{min})	1%	1%
(b)	45%	32%
(c)	55%	68%
(L^A)	21.6 months	45.6 months
n	3 cycles	

In contrast to the amount of research about smartphone lifetime, not so many studies concerned about the number of cycles a phone can be refurbished before entering recycling process. If refurbishment and recycle are taken into account, then the used phone will only serve one cycle by being refursbished, and then eventually being recycled. EESC (2019) did not consider the extended lifetime amount of the phone by reusing or replacing components, while Figge et al. (2018) computed their Combination Matrix with the additional 2 cycles. In the case of Fairphone, since customers can replace the battery themselves that in the end, a Fairphone can be used in 6 years with 2 times of changing the batteries (each battery is assumed to work properly for 2 years) (Güvendik, 2014). Thus, comparing to the ordinary phone, it is equal to 3 cycles in total, with 1 virgin cycle, and 2 refurbished cycles. Therefore, regard to factor (n) as total number of cycles, it will be equal to 3 for both the scenarios.

With the percentage decreased of lifetime of the refurbished phone comparing to the original one – factor (α) – there is no other source except Franklin-Johnson et al. (2016) and Figge et al. (2018) mentioned about this issue. According to both studies, experts gave out the opinion that lifetime of refubished phone is expected to be only 50% comparing to the real lifetime of the virgin phone. However, more and more sellers are supplying refurbished phones with a warranty of 12 months just as same as the one customers can get when purchasing new phones (Leggett, 2020), except the case of refurbished Iphones with only 6 months of warranty. Even with Fairphone, both virgin and refurbished products will be guaranteed within 2 years (Fairphone, 2019). Therefore, since the trend of purchasing refurbished phones from big sellers with full guarantee will increase that there is no factor (α) in this situation.

4.1.3. Data of retained energy and retained emission

Energy for and emission from material flow within the technosphere are seen as two interlinked factors as cause and effect. The more energy required for material to be extracted and turned into usable product the more emission to be released into the atmosphere. Thanks for EoL strategies of waste management and material recovery that less energy is needed and less emission is leaked (UNEP, 2013b).

Data for factors related to computations of retained emission and energy are collected from various sources as until now there is no single article or report measuring and covering all the necessary data. For average weight of each metal within a phone, data from the report of EESC (2019) was taken. Especially, since EESC did not report the weight of nickel (Ni) that data for nickel weight was adopted from the report of Fairphone 2 (Güvendik, 2014). Data for total average weight of a phone is also reported from EESC (2019) as 164 grams. All data for material retained energy are listed in table 5 and material retained emission in table 6.

Data for retained energy consists of following components:

(1) energy needed for material extraction and purification $(en_{extraction})$;
(2) energy for product manufacture and transportation $\left(en_{production}\right)$;
(3) energy for product consumption $(en_{consumption})$;
(4) energy for recycling material $\left(en_{RC\ step}\right)$

The data for (1) is taken from UNEP (2013b) which mainly is computed from ecoinvent database. Only data about energy for metal extraction of tungsten (W) is used from the book of “Thanatia – The destiny of the Earth’s Mineral Resources” (Capilla and Delgado, 2015). Since the unit of data is MJ/kg that it will be multiplied with the weight of material in a phone to attain the energy needed for extracting and purificating that amount of metal to produce a component of a smartphone. Some data have the ranges of variation, thus the median points are calculated and put into brackets for representation.

Data for (2) and (3) are comprised from the work about material and energy consumption of mobile phone in China (Yu et al., 2010). According to Yu et al. (2010) that the energy for production, components assemply, and transportation of a phone is is $120 + 2 + 30 = 152\ MJ$, and the energy for annual consumption of mobile phone is $32.4\ MJ$. The numbers will be multiplied with the average weight of each material in an average phone to gain correct data (2) and (3) for each material. Since energy for consumption is regarded as annual energy intake that two ranges of values are computed for two different scenarios, 1 with 21.6 months and 1 with 45.6 months.

Table 3: Data of saved energy for recycling from different sources

Metal	**Data from UNEP (2013b) (%)**	**Data from BIR (2016) (MJ/kg)**	**Data from Cui and Forssberg (2003) (%)**	**Data from Lupi et al. (2005) (MJ/kg)**	**Chosen data (% of MJ/kg)**
Ag	96	-	-	-	96%
Al	90 – 97	2.4	95	-	95%
Au	98	-	-	-	98%
Co	-	-	-	10.08	10.08 MJ/kg
Cu	84 – 88	6.3	85	-	85%
Fe	60 – 75	11.7	74	-	74%
Ni	90	1.86	-	-	90%
Sn	-	0.2	-	-	0.2 MJ/kg
W	-	-	-	-	50%

Data for (4) is taken from 2 sources due to the lack of some data in each source. UNEP (2013b) mentioned the percentage of saved energy of a unit mass of material by recycling to a number of metals, including those which are scrutinized in the study: Ag, Al, Au, Cu, Fe, Ni. Cui and Forssberg (2003) also reported some percentage of energy saved for Al, Cu, and Fe.

Data for two metals are not mentioned due to the shortage of data of UNEP – Co, and Sn – will be supplemented by the study about recycling nickel and cobalt from lithium-ion batteries (Lupi et al., 2005) and the report of Bureau of International Recycling (2008). Data from Lupi et al. (2005) for recycling cobalt is 2.8 kWh/kg, which when converting to MJ/kg is 10.08 MJ/kg. Only Tungsten (W) does not have the data for the section (4), thus the number of 50% is considered but with only illustrative purposes. After computing the difference of absolute data between energy saved in MJ/kg of BIR (2008) and energy extraction in MJ/kg of UNEP (2013b), the percentage of energy saved is quite similar to what was reported in UNEP (2013b) and Cui and Forssberg (2003). Thus, in the end, the chosen data is pointed out in Table. 3 for unification in computation of $en_{RC\,step}$. Then $en_{RC\,step}$ is computed based on the percentage of energy saved comparing to virgin material extraction. The final result indicates the energy needed to recycle the amount of material in an average smartphone.

Data for retained emission from material circularity are also taken from several sources. As same as the case of retained energy, data for retained emission includes:

(5) emission from material extraction and purification $(em_{extraction})$;
(6) emission from product manufacture and transportation $\left(em_{production}\right)$;
(7) emission from product consumption $\left(em_{consumption}\right)$;
(8) emission from material recycling process $\left(em_{RC\ step}\right)$;

Emission of virgin metal extraction and purification (5) has its data reported from the study about life cycle assessments of metals (Nuss and Eckelman, 2014). However, regarding to gold, other sources provide much higher figures of emission from gold production (Tost et al., 2018; Chen et al., 2018). While Nuss and Eckelman (2014) cited the number of 12,500 kg CO_2-eq/kg gold, the report of gold production in China pointed out the emission of gold is 55,500 kg CO_2-eq/kg gold (Chen et al., 2018) and a review about the impact of metal mining industry on environment reported 23,300 kg CO_2/kg gold (Tost et al., 2018). The number of 23,300 was chosen. Data of emission from gold production varies because of the decreasing ore content (Valero Navazo et al., 2014).

Based on the foundation work of EESC (2019), the emission from production, packaging, and transportation (6) is 56 kg CO_2-eq/phone. The number was conducted by taken the average of emission from different models of phones (EESC, 2019). Other studies also reported the similar amount of emission from mobile phone production (Erkan et al., 2016; Suckling and Lee, 2015). In the case of Fairphone, it is hard to believe that Güvendik gave out the number of only 5.3401 kg CO_2-eq/ Fairphone, and the total emission is 16.044 kg CO_2-eq/ Fairphone. However, another study for applying life cycle assessment to Fairphone resulted in 35.98 kg CO_2-eq in production phase and 43.85 kg CO_2-eq in total emission (Proske et al., 2016). For this study, the number from EESC is still chosen due to the representative ability of an average smartphone, since some documents from Apple cited higher emission of Iphone model (Apple, 2020).

About data for (7) EESC reported the number of 5 kg CO_2-eq/ phone/ year, while Erkan et al. (2016) calculated the range of annual emission from consumption is 17 – 19 kg CO_2-eq/ phone in 3 years, which turns out to be 5.6 – 6.3 kg CO_2-eq/ phone/ year. According to the trend of using smartphones is more daily and typical that 6 kg CO_2-eq/ phone/ year was taken as the annual emission from consumption.

Data for (8) is taken from the report of BIR (2008). However, data was insufficient in the case of Ag, Au, Co, and W. Until now there is no concrete data for these metals (World Gold Council, 2018); thus the percentages of retained energy of the metals are taken, since the more energy is saved, the less emission is released.

Table 4 describes the data for emission from recycling process for metals from various sources. The percentage of saved emission of Cobalt was taken from the difference between energy from recycling process of Cobalt and energy from extraction process of Cobalt.

Table 4: Data of saved emission for recycling from different sources

Metal	**Data from BIR (2008) (kg CO_2/ kg metal)**	**Percentage of saved emission (%)**
Ag	-	96%
Al	0.29	-
Au	-	98%
Co	-	92%
Cu	0.44	-
Fe	0.7	-
Ni	0.22	-
Sn	0.024	-
W	-	50%

Table 5: Data for material energy retainment

Metal	**Weight in phone (gram)**	**Percentage weight of metal in a phone (%)**	$en_{extraction}$ **(MJ/kg)**	$en_{extraction}$ **(MJ/phone)**	$en_{production}$ **(MJ/phone)**	$en_{consumption}$ **(MJ/ phone/ 21.6 months)**	$en_{consumption}$ **(MJ/ phone/ 45.6 months)**	$en_{RC\ step}$ **(MJ/phone)**
Ag	0.21	0.128	1,500	0.315	0.195	0.075	0.158	0.013
Al	31.89	19.445	190 – 230 (210)	6.697	29.557	11.34	23.941	0.335
Au	0.03	0.018	310,000	9.3	0.028	0.011	0.023	0.186
Co	8.35	5.091	130	1.086	7.739	2.969	6.269	0.084
Cu	14.26	8.695	30 – 90 (60)	0.856	13.217	5.071	10.705	0.128
Fe	14.02	8.549	20 – 25 (22.5)	0.315	12.994	4.986	10.525	0.082
Ni	1.87	1.14	180 – 200 (190)	0.355	1.733	0.665	1.404	0.036
Sn	0.1	0.061	250 – 320 (285)	0.029	0.093	0.036	0.075	0.00002
W	0.3	0.183	213 – 369.2 (291.1)	0.087	0.278	0.107	0.225	0.044
Total	**71.03**	**43.311**	**312,688.6**	**19.04**	**65.833**	**25.259**	**53.324**	**0.908**
Sources	*EESC (2019)* *Güvendik (2014)*	*EESC (2019)*	*UNEP (2013b)* *Capilla and Delgado (2015: 215)*	*UNEP (2013b)* *Capilla and Delgado (2015: 215)*	*Yu et al. (2010)*	*Yu et al. (2010)*	*Yu et al. (2010)*	*UNEP (2013b)* *BIR (2008)* *Lupi et al. (2005)* *Cui&Forssberg (2003)*

Table 6: Data for material emission retainment

Metal	**Weight in phone (gram)**	**Percentage weight of metal in a phone (%)**	$em_{extraction}$ **(kg CO_2-eq/kg)**	$em_{extraction}$ **(kg CO_2-eq/phone)**	$em_{production}$ **(kg CO_2-eq/phone)**	$em_{consumption}$ **(kg CO_2eq/phone/ 21.6 months)**	$em_{consumption}$ **(kg CO_2-eq/phone/ 45.6 months)**	$em_{RC\ step}$ **(kg CO_2-eq/phone)**
Ag	0.21	0.128	196	0.041	0.072	0.014	0.029	0.0016
Al	31.89	19.445	8.2	0.261	10.889	2.1	4.433	0.0092
Au	0.03	0.018	23,300	0.699	0.01	0.002	0.004	0.014
Co	8.35	5.091	8.3	0.069	2.851	0.55	1.161	0.0055
Cu	14.26	8.695	2.8	0.04	4.869	0.939	1.982	0.0063
Fe	14.02	8.549	1.5	0.021	4.787	0.923	1.949	0.0098
Ni	1.87	1.14	6.5	0.012	0.639	0.123	0.26	0.0004
Sn	0.1	0.061	17.1	0.0017	0.034	0.0066	0.14	0.000002
W	0.3	0.183	12.6	0.0038	0.102	0.02	0.042	0.051
Total	**71.03**	**43.311**	**23,553**	**1.1485**	**24.253**	**4.6776**	**10**	**0.186**
Sources	*EESC (2019)* *Güvendik (2014)*	*EESC (2019)*	*Nuss&Eckelman (2014)* *Tost et al. (2018)*	*Nuss&Eckelman (2014)* *Tost et al. (2018)*	*EESC (2019)*	*EESC (2019)*	*EESC (2019)*	*BIR (2008)*

4.1.4. Data of retained child labour

Child labour has been one of the darkest consequences of metal mining besides human toxicity, ecotoxicity, waste waster, air pollution, etc. Although child labour has been decreasing gradually, it is still one of the main social problem in under-developed countries where most of them is in Africa, Latin America, and Asia (Ortiz-Ospina and Roser, 2020). However, there is still a lack of literature about measuring positive impacts of circular economy on the social aspect, especially in the case of child labour. From the 9 chosen metals above, only 3 are not related to child labour: Al, Fe, and Ni, due to the vast supply and high recycling rates of these metals. The other 6 – Ag, Au, Co, Cu, Sn, and W – are recorded as metals which are connected to child labour issue (U.S. Department of Labor, 2018a). Due to the availability of data that only 2 out of 6 metals – Gold and Cobalt – are covered in this thesis; as child labour of silver only happens in Bolivia (U.S. Embassy in Bolivia, 2018) and Bolivia is not the top 5 countries of world silver supply (Anthony, 2020). Child labour of copper is only recorded in the Democratic Republic of Congo, yet since copper and cobalt are extracted from the same ore that the problem of child labour is mainly concentrated in the case of cobalt; and as copper is also extracted by several other countries with high recycling ratio. There is not enough available data regarding to the extraction of tungsten and tin.

4.1.4.1. Child labour in cobalt mining

Following the rise of lithium-ion battery, cobalt has been extracted with vast amount to support the green energy transition (Frankel, 2016). Child labour related to cobalt only happens in Democratic Republic of Congo (U.S. Department of Labor, 2018a). Until now, Democratic Republic of Congo is the first country in the world for cobalt production, with 104,000 metric tons in 2018 and 100,000 metric tons in 2019 (Barrera, 2020), thus supplying more than half the amount of cobalt worldwide (Tsurukawa et al., 2011). Among the domestic production of cobalt, ASM produces somewhat from 60% to 90% of total cobalt in Democratic Republic of Congo (Tsurukawa et al., 2011). Therefore, the average weight of ASM cobalt production on the total domestic production is approximately 75%.

Child labour has been recorded in Democratic Republic of Congo since the end of the 20th century (Tsurukawa et al., 2011), yet until the 21st century that the number of children in mining industry has increased due to the global demand of cobalt. As the form of ASM is legal in Democratic Republic of Congo that children are needed in the mines due to various reasons, from poor family's financial condition to child trafficking and forced labour (Hahn et al., 2013). Although there are some investigations about child-labour in cobalt mines, the figures varies between the studies. According to the study of Tsurukawa et al., 28,000 to 45,000 children are working as miners in the cobalt-copper belt in Democratic Republic of Congo (2011), while two-third of them are under 15 years old and the other third is from 15 to 17 years old. The research of Faber et al. (2017) cited the number of children in labour ranging from 20,000 to 40,000, which takes about 40% of total labour within the ASM industry. Moreover, Frankel (2016) stated that there are more than 40,000 children extracting cobalt in 2012. For the purpose of estimation and illustration, the number of 40,000 children is chosen.

Tsurumaka et al. (2011) delivered the number of working hours per day of an adult miner is 9 hourse, while the other investigation reported children working load with the range from 36 to 38 hours/ week, which equals to approximately 6 hours/ day (Faber et al., 2017).

To calculate the working hours of children in child labour to produce cobalt, we will follow equation (31). From the data of cobalt mine production of DR Congo, the average production from 2010 until 2019 is 69.4 tonne cobalt (Statista, 2020) or 69,400 kg annually, in which 75% is supplied by the ASM, and 40% of ASM miners are children. Approximately in the cobalt industry, 35,000 children are working everyday for 6 hours, which sum up about 2000 hours every year after subtracting an amount of days for holiday, rests, etc. Thus, we can have:

$$H^{Co} = \frac{40000 \times 2000}{69400 \times 70\% \times 40\%} = 4{,}117\, hrs/kg\, Co = \ 4.1\ hrs/g\ Co$$

As we can see, each gram cobalt needs 4.1 hours of child labour to be extracted and purified. While a smartphone requires 8.35 gram cobalt, a laptop needs 1 ounce or 28.35 gram cobalt and a typical electric car consumes 10 – 20 pounds or 4.5 – 9 kg cobalt; which indeed needs the children to work for 34 hours, 116 hours, and 18,526 – 37,053 hours of working.

4.1.4.2. *Child labour in gold mining*

The global picture of child labour for gold is a thousand times larger than the picture for cobalt. Children involving in the mining and quarrying industry in all over the world mainly extract and purify gold due to its precious and prestigious values. If child labour of cobalt only exists in 1 country, then child labour of gold exists in total 22 countries, spreading from Latin America to Africa and Asia (U.S. Department of Labor, 2018a). Another study claimed that child labour in gold extraction spreads not to 22 but upto 26 countries in total (Schipper and de Haan, 2015). Figure 10 depicts the seriousness of child labour in gold extraction. Since the number of countries is huge that gathering data from each country and computing for the global picture will be impossible within the scope of this thesis. Therefore, another method was approached to calculate the average working hours of child labour for a unit mass of gold.

Fortunately, a study of child labour in gold mining was conducted in the global scale (Schipper and de Haan, 2015). The number of children involving in gold mining has surpassed the thresold of 1 million due to the rising demand in gold, yet for calculating purpose this number is used later. As same as ASM in cobalt mining, the percentage of children in gold mining ranges from 30 – 50%, thus the rate of 40% is chosen. A child also works 6 hours/ day and thus about 2000 hours/ year. According to Schipper and de Haan, ASM contributes about 15 to 20% of global gold supply, thus an average weight number of 17.5% is chosen for illustrative purpose. Regard to the global gold production, data is taken from the dataset Goldhub (Goldhub, 2020). The average global production from 2010 to 2018 is calculated from the dataset and the result is 3,176.2 tonne or 3,176,199 kg gold annually. Applying data to equation (31), we can have:

$$H^{Au} = \frac{1000000 \times 2000}{3176199 \times 17.5\% \times 40\%} = 8{,}995.5\ hours/kg\ Au \approx 9\ hours/g\ Au$$

From the calculation above, each gram gold requires 9 hours of child labour, more than double the necessary time of child labour for cobalt mining. Actually, the number is believed to be much higher, yet due to the internal issues within the ASM mining that accurate numbers are difficult to achieve.

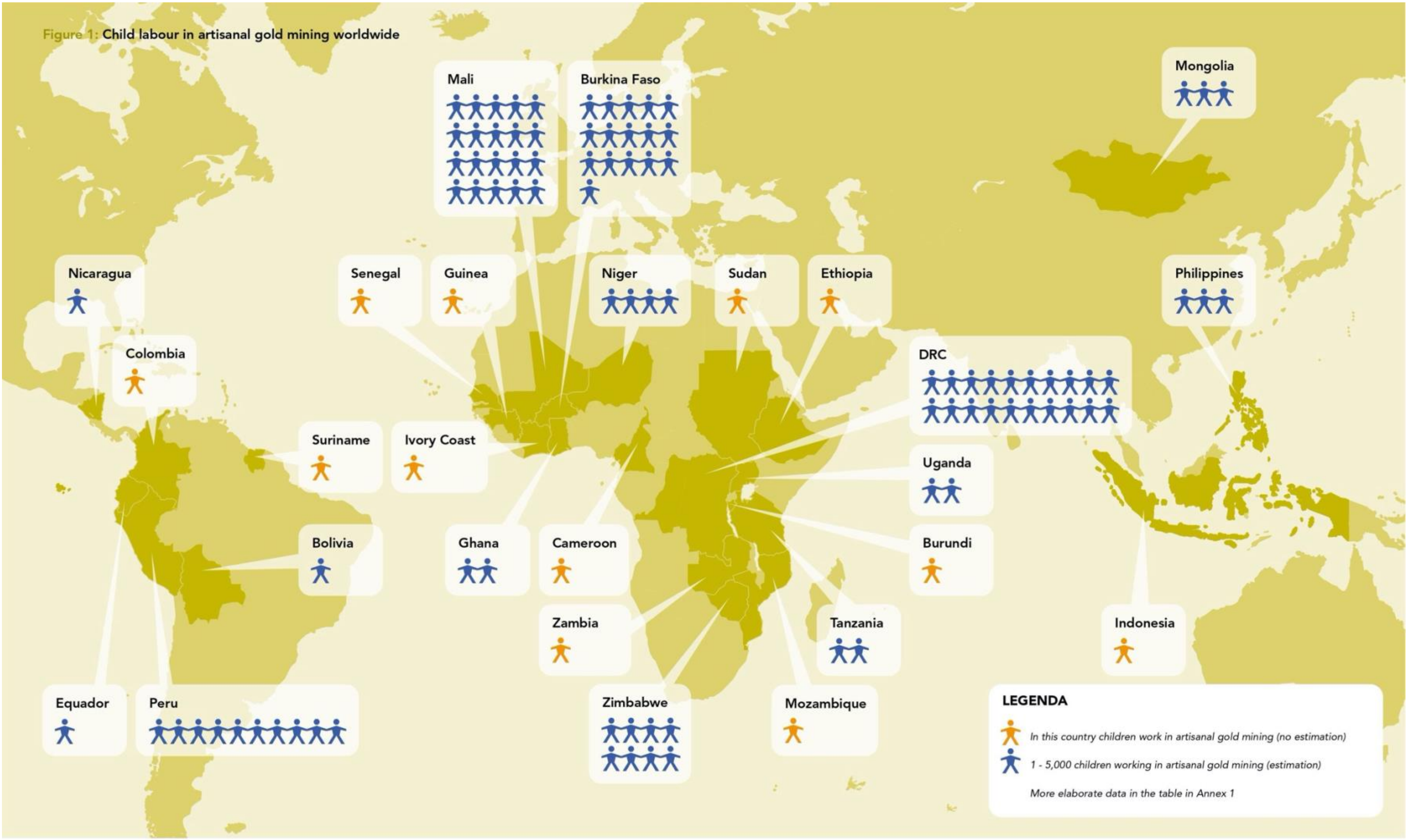


Figure 10: Intensity of child labour in gold mining in different countries (Schipper and de Haan, 2015: 24)

4.2. Result interpretation and discussion

Applying the collected and computed data above, material circularity, longevity, and other related issues are calculated to illustrate the difference between practical and ideal scenarios.

4.2.1. Scenario 1

Within the first scenario, the collected rate of mobile phone (a) is 22%, in which 45% is refurbished (b) and 55% is recycled (c). With the total of cycles is 3 (n), circularity of each metal is computed in table 7. The minimum expanded circularity is of Fe and W, while the maximum expanded circularity is of Au, Cu, and Ni. The reason of this difference in circularity lies in the recycling ratio of particular metal, with Fe and W are the lowest (although in fact the amount of recycled Fe is huge in the society, within the case of smartphone copper was chosen as the bearer material for recycling, thus leading to the lost of Fe).

To calculate the maximum cycles that the metal can last before being obsolete, equation (12) was applied with the input of factor (v) and (u). However, since the returned ratio is only 22% and the smallest assumed returned ratio (a_{min}) is 1% that the maximum of cycles a metal can circulate is also about 3 cycles. Thus, the calculation for maximum cycles a metal can reach does not work in this scenario.

Regarding to material longevity, product refurbishing and metal recycling extends the lifetime of metal from 21.6 months upto 27.2 months. Circularity within 3 cycles also reduces the impact of emission and energy, as retained emission of one phone ranges from 0.034 kg CO_2-eq of Tin to 10.077 kg CO_2-eq of Aluminium, and retained energy of one phone ranges from 0.137 MJ of Tungsten to 33.678 MJ of Aluminium. Child labour is also reduced, yet since the amount of gold in each phone is too small (0.03g Au/ phone) that 3 circulated cycles only reduces 0.07 hours of child labour in gold mining. Nonetheless, from the research of EESC (2019), in 182 million of phones sold in 2017 there is the estimation of 22 millions of phones will enter recycling, which can help to retain 1,540,000 hours of child labour in gold ming. In the case of cobalt, it can save 8.35 hours of child labour in cobalt mining from every circulated phone.

Table 7: Material circularity, longevity, retained emission and energy, and child labour of realistic scenario

Metal	**Circularity**	**factor (v)**	**factor (u)**	**max n**	**Longevity (months)**	EM_{RF}	EM_{RC}	**Retained emission (kg CO_2-eq)**	EN_{RF}	EN_{RC}	**Retained energy (MJ)**	**Retained Child labour (hours)**
Ag	1.226	0.18975	0.008625	2.85	26.476	0.113	0.0296	0.134	0.51	0.227	0.708	
Al	1.131	0.11715	0.005325	2.44	24.427	11.15	0.0378	10.077	36.254	0.954	33.678	
Au	1.26	0.21395	0.009725	3	27.21	0.709	0.6508	1.354	9.328	8.658	17.919	0.07
Co	1.243	0.20185	0.009175	2.93	26.84	2.92	0.054	2.687	8.825	0.852	8.879	8.305
Cu	1.26	0.21395	0.009725	3	27.21	4.909	0.032	4.453	14.073	0.692	13.426	
Fe	1.116	0.10505	0.004775	2.37	24.107	4.808	0.0006	4.328	13.309	0.012	11.991	
Ni	1.26	0.21395	0.009725	3	27.21	0.651	0.011	0.598	2.088	0.303	2.213	
Sn	1.243	0.20185	0.009175	2.93	26.84	0.357	0.0014	0.034	0.122	0.025	0.137	
W	1.116	0.10505	0.004775	2.37	24.107	0.1058	-0.0024	0.093	0.365	0.0022	0.331	

4.2.2. Scenario 2

The second scenario is more interesting (table 8 and 9), since the collected rate of mobile phone (a) is 95%, in which 32% is refurbished (b) and 68% is recycled (c). Although the number of cycles (n) for each metal is 3, the maximum cycle a metal can reach before being obsolete varies between materials.

In a normal sense, circularity increases from 44% in the case of Fe and W, yet the other metals have their added circularity upto 158% (Co and Sn) and 176% (Au, Cu and Ni). This leads to the increase of metal longevity from the 1st cycle of 21.6 months to the circulated longevity of minimum 66.09 months or 5.5 years (Fe and W) and maximum 125.85 months or 10.5 years (Au, Cu, and Ni). Circularity in 2 added cycles also diminishes the impact of emission and energy, as retained emission of one phone ranges from 0.025 kg CO_2-eq of Tin to 7.187 kg CO_2-eq of Aluminium, and retained energy of one phone ranges from 0.11 MJ of Tungsten to 24.5 MJ of Aluminium. The reason which leads to the decrease of retained emission and energy in the 2nd scenario comparing to the 1st one is because of the imbalance between refurbishment rate of returned phones (b) and recycled rate of returned phones (c). Additionally, product refurbishment saves more energy and emission than product recycling. Retained child labour reached the higher points comparing to the practical scenario, with 3 cycles of refurbishing and recycling saves 0.48 hours of child labour in gold mining and 54.12 hours in cobalt mining.

In a special condition where maximum circulated cycles are computed from factor (u) and (v), the ideal picture is depicted clearer. Several metals can last upto 30 (Co and Sn) and 54 cycles (Au, Cu, and Ni). This results in maximum circularity of several metals escalate to 4.687 (Ag), 6.749 (Co and Sn), and 12.033 (Au, Cu, and Ni) and maximum longevity of materials as 17.8 years (Ag), 25.65 years (Co and Sn), and even 45.73 years (Au, Cu, and Ni). Due to the fact that materials are circulated longer in the technosphere that much emission and energy are retained, stopping the release of 17.97 kg CO_2-eq of Aluminium, 28.16 kg CO_2-eq of Cobalt, 35.48 kg CO_2-eq of Gold, and 84.41 kg CO_2-eq of Copper, and saving 61.25 MJ of Aluminium, 98.69 MJ of Cobalt, 263.6 MJ of Copper, and even 470.25 MJ of Gold. Furthermore, 2.98 hours of child labour in gold mining and 196.82 hours in cobalt mining can be halted thanks to the maximum in material circularity.

Table 8: Material circularity, longevity, retained emission and energy, and child labour of ideal scenario

Metal	**Circularity**	**Longevity (months)**	**Longevity (years)**	EM_{RF}	EM_{RC}	**Retained emission (kg CO2-eq)**	EN_{RF}	EN_{RC}	**Retained energy (MJ)**	**Retained Child labour (hours)**
Ag	2.41	109.907	9.16	0.113	0.0296	0.113	0.51	0.227	0.634	
Al	1.562	71.21	5.93	11.15	0.0378	7.187	36.254	0.954	24.5	
Au	2.76	125.85	10.49	0.709	0.6508	1.339	9.328	8.658	17.745	0.48
Co	2.581	117.688	9.81	2.92	0.054	1.942	8.825	0.852	6.806	54.12
Cu	2.76	125.85	10.49	4.909	0.032	3.185	14.073	0.692	9.947	
Fe	1.45	66.093	5.508	4.808	0.0006	3.078	13.309	0.012	8.534	
Ni	2.76	125.85	10.49	0.651	0.011	0.432	2.088	0.303	1.7485	
Sn	2.581	117.688	9.81	0.357	0.0014	0.025	0.122	0.025	0.112	
W	1.45	66.093	5.508	0.1058	-0.0024	0.065	0.365	0.0022	0.237	

Table 9: Material circularity, longevity, retained emission and energy, and child labour with maximum potential

Metal	**Max n**	**Max Circularity**	**Max Longevity (months)**	**Max Longevity (years)**	EM_{RF}	EM_{RC}	**Max Retained emission (kg CO_2-eq)**	EN_{RF}	EN_{RC}	**Max Retained energy (MJ)**	**Max Retained Child labour (hours)**
Ag	20	4.687	213.73	17.81	0.113	0.0296	1.069	0.51	0.227	6.03	
Al	6	1.66	75.7	6.31	11.15	0.0378	17.968	36.254	0.954	61.25	
Au	54	12.033	548.71	45.73	0.709	0.6508	35.478	9.328	8.658	470.25	2.98
Co	30	6.749	307.76	25.65	2.92	0.054	28.162	8.825	0.852	98.69	196.82
Cu	54	12.033	548.75	45.73	4.909	0.032	84.41	14.073	0.692	263.6	
Fe	5	1.5	68.4	5.7	4.808	0.0006	6.156	13.309	0.012	17.067	
Ni	54	12.033	548.75	45.73	0.651	0.011	11.438	2.088	0.303	46.33	
Sn	30	6.749	307.76	25.65	0.357	0.0014	0.36	0.122	0.025	1.618	
W	5	1.5	68.4	5.7	0.1058	-0.0024	0.13	0.365	0.0022	0.473	

4.2.3. Discussion

From the two scenarios above, we can split the 2nd one into 2 sub-scenarios: 2a (ideal scenario) and 2b (max scenario). Based on the computed result, due to the fact of smaller returned ratio of phone (factor (a)) that there is no maximum circulation times of metal in the 1st scenario. Moreover, it is also because of higher percentage of returned phones in the 2nd scenario that all calculated figures, from circularity unit retained values of energy and emission, are higher than the figures of the 1st scenario. Comparing between 2 sub-scenarios 2a and 2b, 2b is the best scenario that one wants to achieve due to the maximization of circulation and other values, yet it is not practical because of the consumption behaviour currently. From the surveys of consumer behaviours towards disposing smartphones after usage, more than half of the respondents keep the used electronic devices at home, thus hugely decreasing factor (a) (Uyttenbroek, 2017; European Commission, 2018b; EESC, 2019; Martela, 2019). **Therefore, scenario 2a is the ideal and achievable scenario which policy-makers can consider and apply.**

Adapting the example of gold from Combination Matrix (Figge et al., 2018), illustrative combination of circularity and longevity of 8 metals are depicted in Figure 11 and 12. All the scenarios are graphed to compare the difference of factor (a) and maximum potential circulation times (max n). For easy depiction, longevity takes the unit of years, so 21.6 months is 1.8 years and 45.6 months is 3.8 years. After the first cycle, metal circularity takes the value of 1. From both figures, there is a big positive difference between scenario 1 and 2a, as the magnitudes of circularity and longevity are increased vastly. In some cases, the maximum potential circulation time does not affect much the extension of circularity and longevity (in the case of Al and Fe). In other cases, if the policy of returning phones are tightened strictly, positive impacts of material circularity and longevity is acumulated vastly (Au, Co, Cu, Ni, Sn).

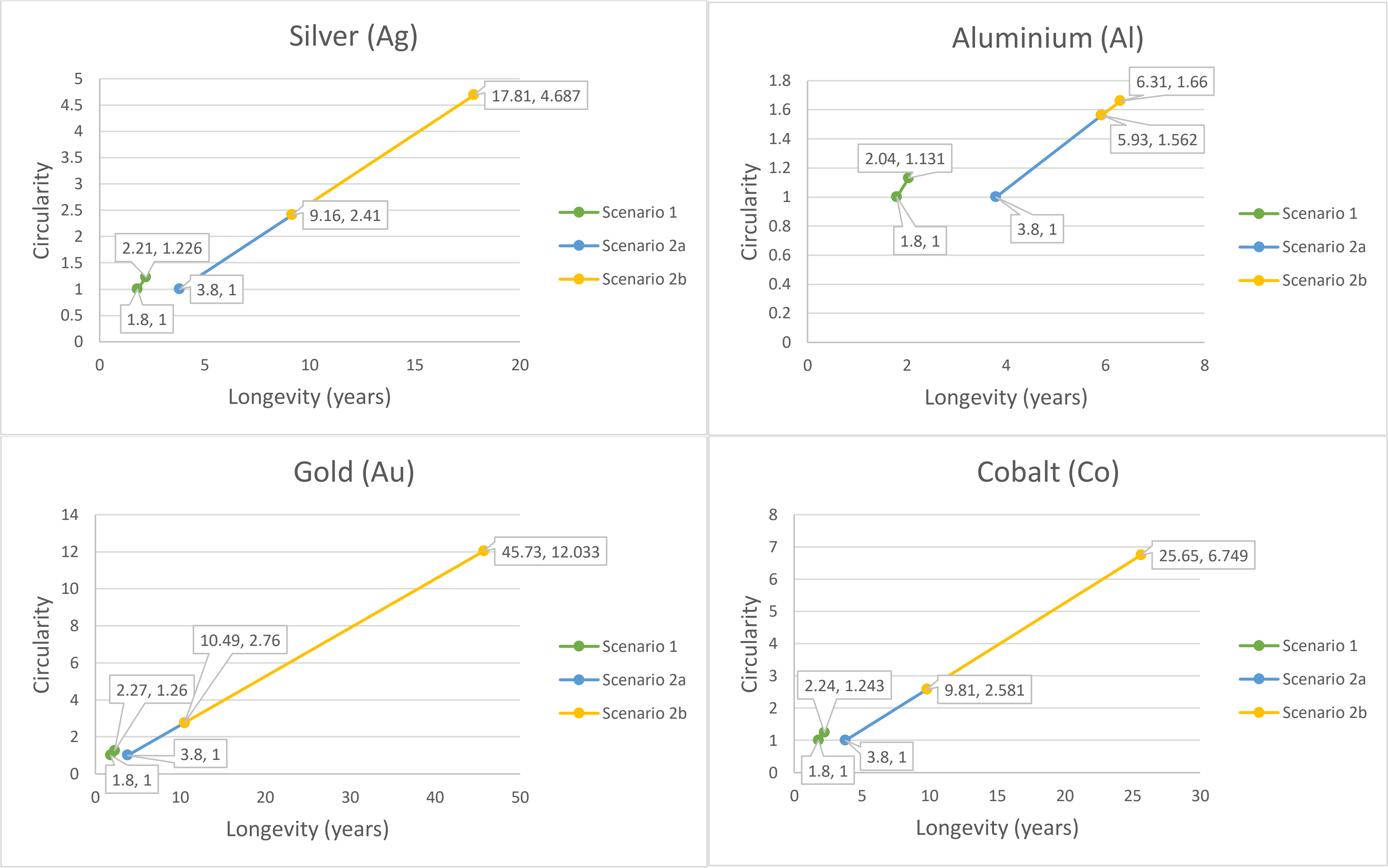


Figure 11: Circularity and Longevity of Silver, Aluminium, Gold, and Cobalt in 3 scenarios

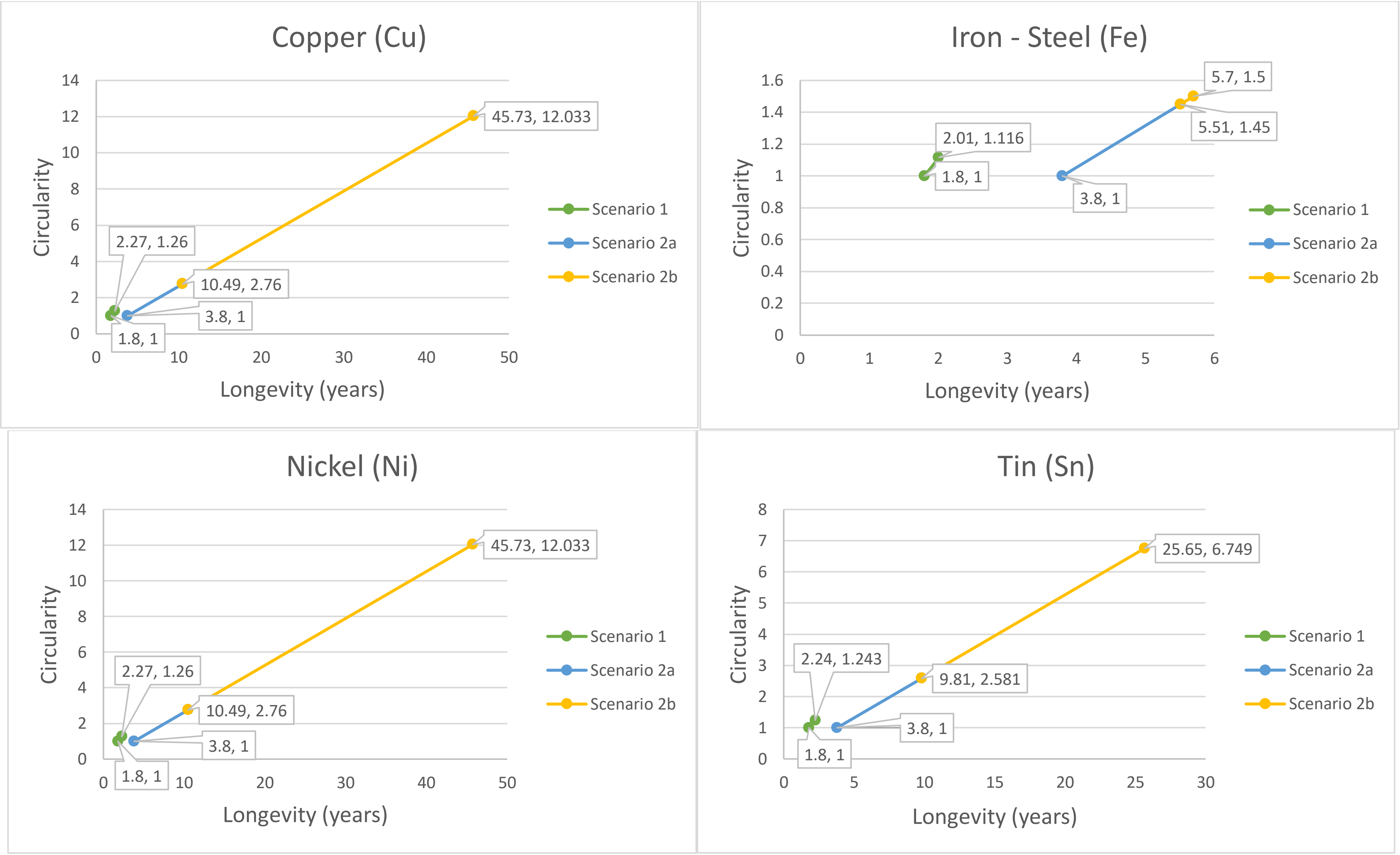


Figure 12: Circularity and Longevity of Copper, Iron/Steel, Nickel, and Tin in 3 scenarios

Regarding to circularity, Figure 13 shows that Au, Cu, and Ni have the highest circulation in all 3 scenarios due to possessing high material recycling rate (factor (d)). Circularity units of Al, Fe, and W do not adjust much through out 3 scenarios because of small material recycling rates.

Since material circularity affects material longevity that the results of longevity are similar to circularity. Thus, according to Figure 14, it is proper to state that the more times materials can circulate within the economy, the longer materials can stay in the technosphere and constitute products' utility.

Retained values also benefits from circularity of metals, as refurbishing and recycling strategies assist in releasing less emission and saving more energy (Figure 15 and 16). It is interesting that with although copper (Cu) saves the most emission in scenario 2b, in the two other cases aluminium (Al) retains the most of CO_2. This phenomenon was caused since in scenario 2b, Cu has the highest value in maximum of factor (n) and factor (d). In the aspect of energy, gold (Au) retains the highest amount of energy in scenario 2b, while aluminium (Al) is the winner of energy retainment in two other scenarios. When investigating deeper in the retained energy values of two particular strategies, refurbishment tends to save more energy and emission than recycle in all 3 scenarios (Table 7, 8 and 9). Especially, retained emission of tungsten takes the negative values in all 3 scenarios, supporting the fact that recycling phase in the most cases (but not in all the cases) releases less emission than extracting and purifying phase (UNEP, 2013a: 83).

Child labour is also benefited from material circulation as the amount of retained working hours of a child increases from the 1st to the 3rd scenario (Figure 17). Although gold takes more time for a child to mine than cobalt, since the amount of gold in a phone is too low (0.03%) while the amount of cobalt is 8.35g that returning smarphones for re-use and recycle reduces more child effort in cobalt. Scenario 1 retains 8.35 hours of child labour, while scenario 2 retains upto 54.12 hours (more than 1 working week), and the last scenario retains 196.82 hours (nearly 1 and half working months).

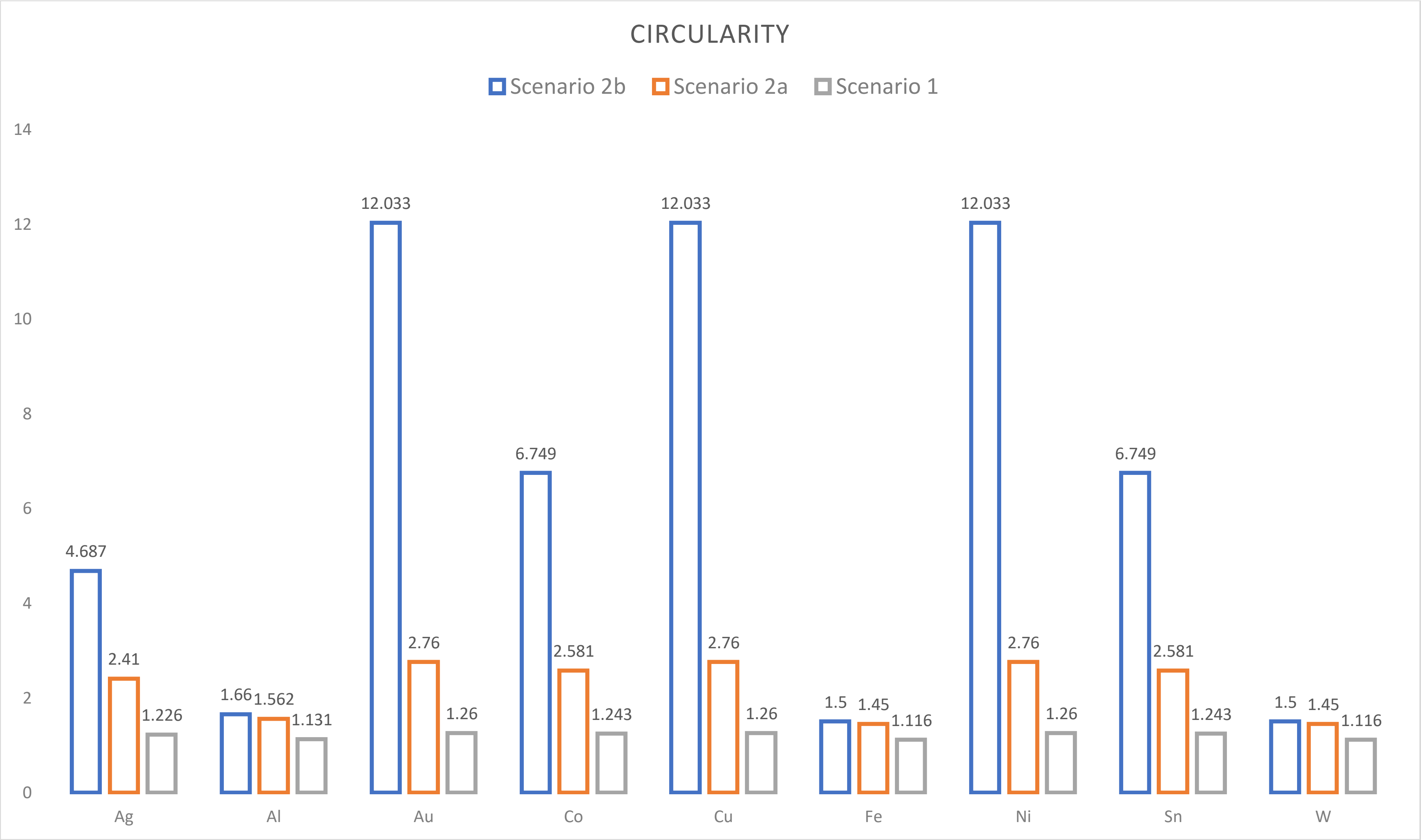


Figure 13: Material Circularity of 9 metals in 3 scenarios

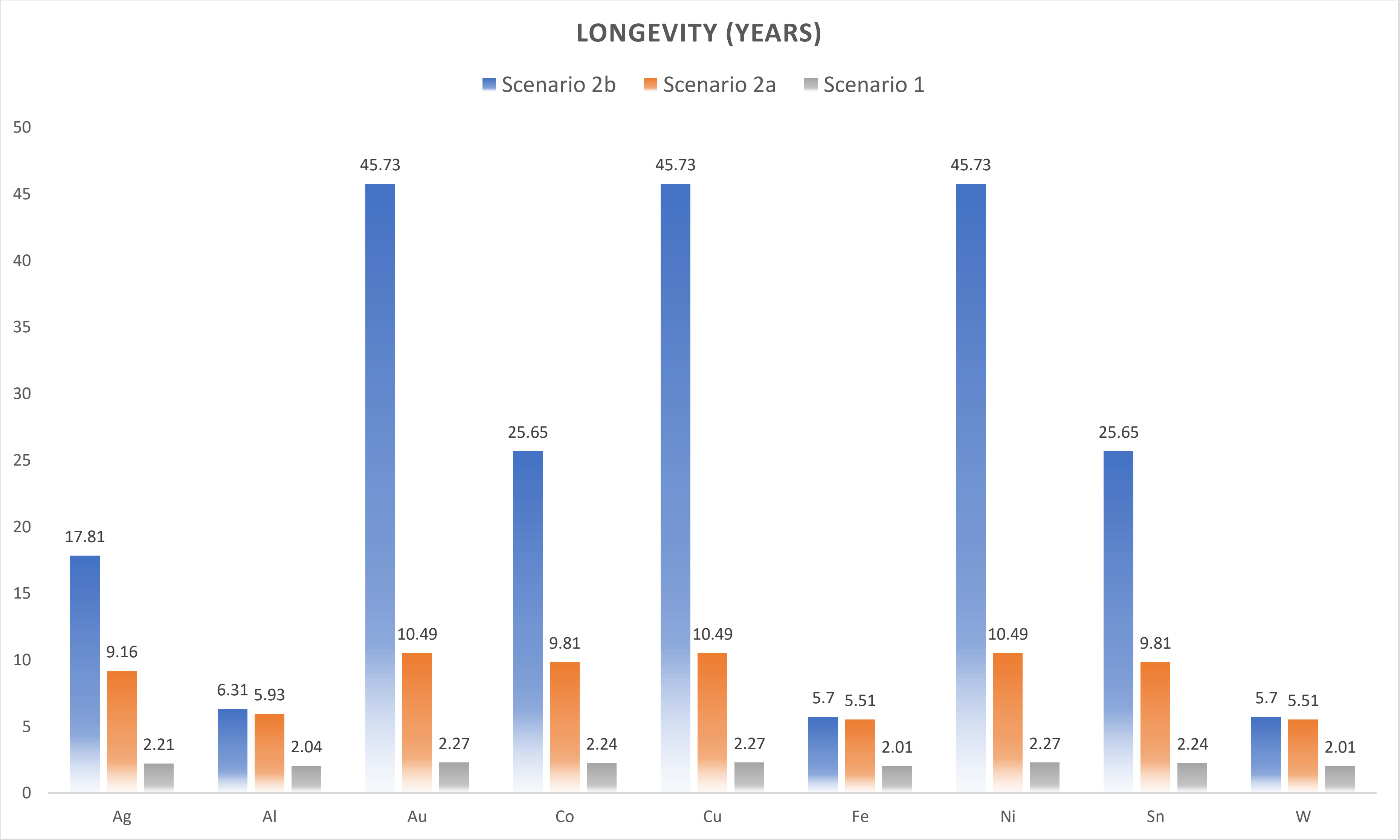


Figure 14: Material Longevity of 9 metals in 3 scenarios

Figure 15: Retained emission of 9 metals in 3 scenarios

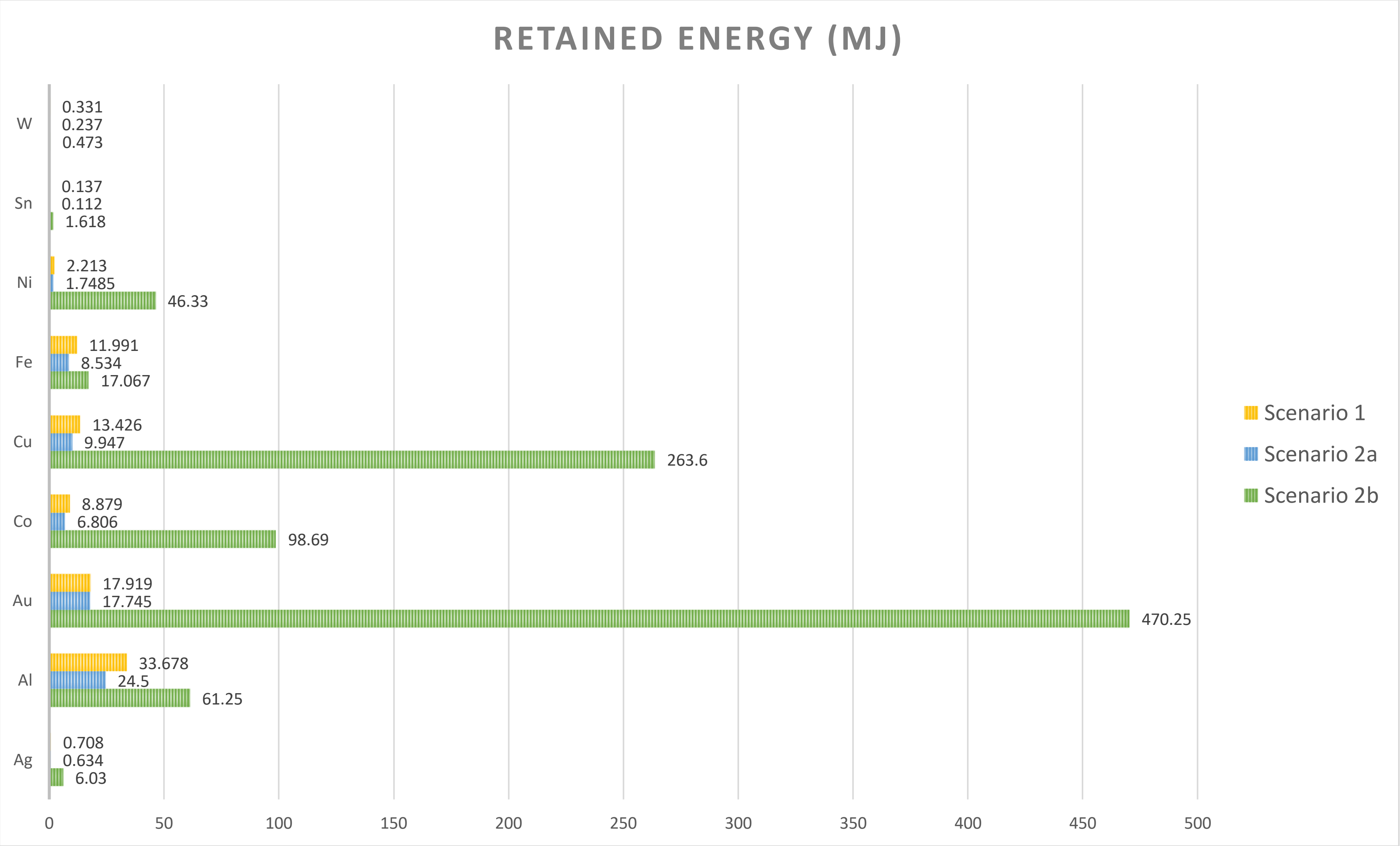


Figure 16: Retained energy of 9 metals in 3 scenarios

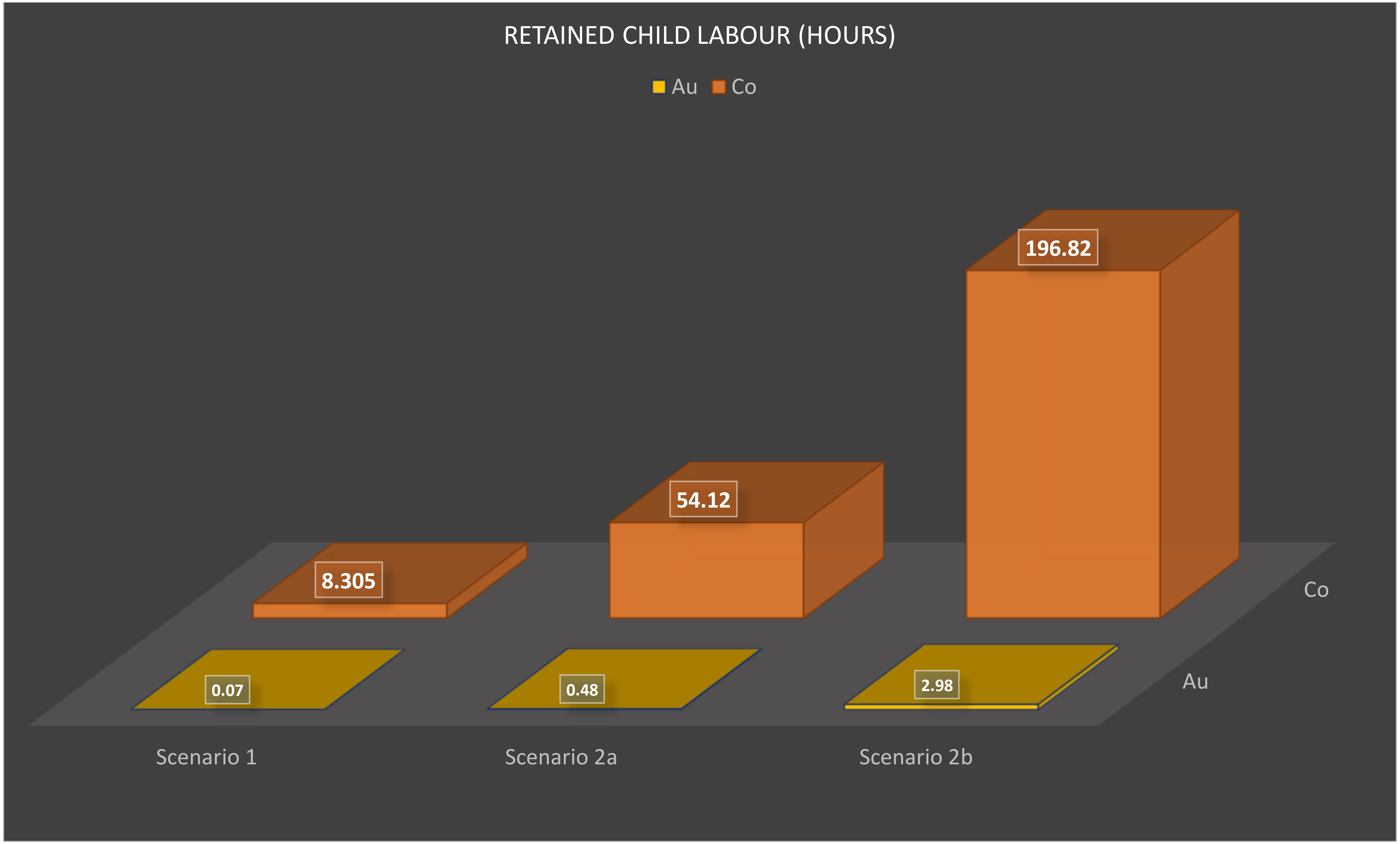


Figure 17: Retained child labour of Gold and Cobalt in 3 scenarios

5. POLICY IMPLICATION

After using the Material Criticality Metrics Chain (MCMC) for the case of smartphone, material circularity, longevity, retained emission and energy of 9 metals have been computed above. Moreover, retained child labour of 2 precious elements is also addressed as the positive consequence of great waste management through refurbishment and recycling. Since there is a huge difference in WEEE regulations between nations (UNEP, 2013a, 2013b; ITU, 2017) that more effort is necessary from policy-makers to ensure high circularity ratios of materials.

As from the calculating formula of material circularity, factor (a) can be seen as the most crucial factors in maintaining materials inside the loop. Several studies have pointed out the low returned rates of electronic and electrical products, such as in the case of smartphone (Uyttenbroek, 2017; Figge et al., 2018; European Commission, 2018b; EESC, 2019; Martela, 2019). As showing from the example, low magnitude of factor (a) leads to low circularity, thus shortening the longevity of material and decreasing the positive effect on retained emission, energy, and child labour. The second important factor in the whole group of indicators MCMC is factor (d). The recycling ratio will depend on several elements, not only technological but also economical feasibility (UNEP, 2013a). **Therefore, policies to encourage returning electrical products and incentives for developing recycling technologies are crucial to increase the magnitude of factor $(\boldsymbol{a})$ and $(\boldsymbol{d})$.**

Besides, product lifetime is also a big issue relating to planned obsolescence and material longevity. Comparing two main scenarios from the example, the ideal scenario has the product lifetime (45.6 months) 2 times longer than of the practical scenario (21.6 months). This influences the results of material longevity of not one single metal but all the metals and compounds constituted the product. Tight co-operation between consumers' unions can also drive the change of product longevity in the future.

The policies for strengthening material circularity and longevity can be promoted by various actors within the product supply chain. **Manufacturers and suppliers can give out incentives for customers to return used products.** Apple and Fairphone are famous with their trade-in or take-back programs, in which customers can receive an amount of money or coupon/ discount for the next purchase when returning used smartphones to the company (Apple, 2019;

Fairphone, 2019). Moreover, Apple is claiming that they are trying to make their products last longer, while Fairphone designs their smartphone with the method of modular-separation, which can lead to easy and self replacement for customers. **Other actors such as government/ state should have stricter rules and incentives about hibernating electrical products, EEE products gathering, and WEEE refurbishing and recycling processes**. In case of not knowing where to start in drafting policies for WEEE, **one should start with making tools to measure the amount of WEEE in the community, state, or one's country**, since WEEE data is only available in 41 countries (ITU, 2017). Until now, only 66% of countries are conducting national e-waste management legislations. Although more than 2/3 of total nations are trying to adapt and form WEEE laws, **regional and international standards are still necessary for the benefit of all nations**, as now there is still the trend of exporting WEEE from developed countries to developing and under-developed countries under the name of recycling (although nearly half of the exported waste are impossible to recycle) (ITU, 2017). Furthermore, **regulations to encourage more start-ups in waste management aspects is also required** as these new organizations and companies are the symbols of innovative business models of the circular economy concept. When the loop of material is tightened, not only challenges in keeping the metals inside the technosphere are revealed but also the opportunities for new business models to enter the waste management industry are exposed.

Regarding consumer behaviour, **it is obvious that policy-makers cannot depend on the perception of consumers about handling e-waste**, due to the fact that their behaviours are much constrained by financial and educational background. Moreover, because of Desirability Planned Obsolescence that customers tend to follow new trends thus purchasing more innovative goods even when the products they are using are still well-functioned (Packard, 1960). Yet, it is hard to have legislations that preventing new innovative products to be commercialized. Another point is that at the time of purchasing, consumers are usually not informed clearly and thoroughly of what to do when the product is collapsed or how to dispose them properly. Thus, **clear information about WEEE management needs to be showed to consumers before the time of purchasing and during the time of experiencing the products**. With the co-operation among all the actors within the supply chain will enhance material circularity.

Relating to the problem of child labour, it is more sophisticated because of different causes. Research has pointed out that not all of child labour is forced labour, and not all child labour is illegal or has to deal with toxic substances and hazardous work (ILO, 2017; U.S. Department of Labor, 2018c). Moreover, many children have to enter the work force, not only in mining and extracting but also in agriculture and service industries due to family financial situation and school fees. More and more supports have been made in several decades for child labour issue (U.S. Department of Labor, 2018a, 2018c), yet the number of working children is still high. **Thus, to solve this problem, this is not only by supporting children whose families have financial issues but also about supporting the economy and legislations of those under-developed countries.** Free education for children in need is also indispensable, and thus it is being conducted in several Latin America and Africa countries (U.S. Department of Labor, 2018c). **It is fortunate that one of the main reason to drive those children into mining and thus hazardous work is because of the demand of precious and essential metals, with which can be eased and gradually solved by high material circularity and longevity rates.**

6. CONCLUSION

This study addresses two main elements of circular economy – circularity and longevity – by forming the Material Circularity Metrics Chain. MCMC is the group of indicators which measures material circulation and lastingness, following with their positive effect as retained emission, energy, and child labour. The effort of building the new group of indicators aims to fill the gap of the linear economy model in which waste is not seen as a resource and growth has to depend on planned obsolescence. By using Inductive research strategy, 5 metrics are formed which are based on the work of Combination Matrix of Figge et al. (2018) and the equations are the answers for the research questions.

There are several contributions of the study to the vast amount literature of circular economy indicators. As mentioned in the 2nd section, although circular economy indicators have been created and formed for decades, they concentrate mainly in the Re-framework, waste management, resource management, and economic efficiency of the concept. Until now there are only 2 works that addressed material circularity, which are the Material Circularity Indicator (MCI) and the Combination Matrix (CM) (EMF, 2015b; Figge et al., 2018). **Therefore, this work of the MCMC is the 3rd study about material circularity**, which is in line with the logic agreed in Figge et al. (2018) that circularity should be interpreted as the number of times the material circulates. However, Figge et al. (2018) did not solve the question of material circularity within the economy, only stop at when the material from the virgin product is recycled. Thus, it did not express how the material travels throughout the technosphere until it becomes obsolete. **MCMC addressed this deficiency by two methodology expansions, first as computing material circularity without stopping material flow at the recycle process (but including it), and second as calculating the maximum potential times that material can flow (max n), leading to the full picture of material circulation. Furthermore, material longevity is seen as an interval of metal lifetime with minimum and maximum range**, depending on the difference of lifetime of refurbished product and recycled product (factor alpha (α)). **Another contribution of this study is about retained child labour working hours,** which has not yet been calculated in any indicator before. There are two reasons that MCMC tried to calculate retained child labour: (1) because of the linkage of circular economy concept with the 3 sustainable development pillars (environment, economy, society); and (2) because child labour is a terrible result of high demand of metals and lack of financial support for the poor and the youth in under-developed countries. It has been shown that the more material can stay inside the technosphere, the less demand of metal will be, then the more child labour working hours can be saved and retained.

Not only material circularity will obviously extend the lifetime of material, decrease emission and energy from products' supply chains, and retain more child labour, but it will also create more jobs for the economy. Since much more effort is needed in collecting, refurbishing and recycling products that opportunities for innovative business are revealed gradually when circular economy is conducted and embedded within societies. Therefore, **material circularity and longevity in particular, or the circular economy concept in general, can be one of the most important leverages which eventually supports and sustains the economy**. The concept is indeed the answer for the pure purpose of Bernard London – to keep the flows of products within the economy. Yet it does not require or accept planned obsolescence but elevates the privilege of materials and metals, respects consumer rights of using and keeping the products, and maintaining the values of non-renewable sources within the technosphere. Products can be used longer, values of metals will be kept inside the economy, and finally we can decouple growth from the environment (Raworth, 2017). In the end, growth can still be sustained without negative influence towards the environment.

Further studies can be developed from limitations of this work. Since the circular economy concept covers too many aspects that several important elements are not addressed by the MCMC, such as financial benefit from material circularity. It is believed that refurbishment and recycle strategies can be the great channels for financial saving, and also for environmental investments. Moreover, the study did not mention the energy and emission of the refurbishment step and the taking-back phase, since it is usually quite smaller than the energy and emission of the extraction – production phases. Although the results may not be altered, yet in the future other studies can develop and fulfil this gap, especially when data is more available. Lastly, it is assumed that the recycled products are the same kind with the virgin ones (as recycled metals are for producing smartphones again). In case of computing material circularity and longevity when products are repurposing and recycled into other kinds of products, more scrutinization and adjustment are necessary.

7. REFERENCE

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