The challenges of recycling critical raw materials and analyzing the alternatives

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Abstract

Low recyclability of the products can cause a dreadful situation for the environment, health and finance. A magnificent amount of e-wastes becomes free to the environment every year. Amongst those wastes, there are also a huge amount of critical raw materials such as indium, gallium, and cobalt exposed to the habitat. These CRMs are very crucial for the mobile phone industry. There are ample amount of reasons to address these materials as critical raw materials. However, the most important ones are insufficient collection, not mandating the policy properly and lack of recycling techniques. The research is made to tackle this problem and help the companies to reduce their waste by extracting more CRMs from the used products. A system dynamic tool called insight maker is used for modeling. The model helped to statistically analyze how the collection of the End of Use (EOU) and End of Life (EOL) could be increased and how the existing recycling process could end up with a great amount of critical raw materials. After simulating the model, it has been found that improved recycling technology certainly increases the stock of critical raw materials. At the very end of this paper, some replacements are discussed for the specified CRMs. Some interesting insights have been found including a very critical material indium is already replaced by graphene.

Keywords— E-waste, CRM, Recycling, Smartphone industry, Metals, Indium, Cobalt, Magnesium, Gallium, Lithium, Environment, Policy, Insight maker

1 Introduction

In this modern age, people tend to use a lot of devices such as computers, smartphones, and radios for their daily activities. It is unfortunate that people have less idea about the materials used in those devices and the impact of these materials on the environment. The following materials have been used such as the display of a mobile phone made of indium material, the extensive use of cobalt for a smartphone's microchips, or the use of lithium-ion in the mobile phone battery. Including these materials, there are some other materials such as Magnesium, Nickle, Gallium tantalum and so on which are recognized as critical raw materials. The reasons behind this recognition are these materials hardly have substitutes due to their unique and reliable properties and they are not available or equally distributed throughout the world. Furthermore, different production companies consume the same critical raw materials that are associated with a risk of supply shortage[17]. Regardless of having such a critical supply chain of the materials, there are quite a lot of phones thrown into the environment. Many research has shown that a great number of e-wastes are dumped because of their company's ineffective recycling strategy or the consumer's negligence to return [13] [28] [20].

Therefore, this paper aims to find the challenges that are associated with the recycling of the critical raw materials and provide some alternatives by statistical analysis of existing recycling data. A study has reported that in 2019, more than 53.7 Million e-waste was generated world wide, and the prediction of the increment of this number is on the line [27]. The mobile phone e-waste has been reported to be more than 4.4 Million which is on average 8.8 percent of overall e-waste throughout the world [25]. Many smartphone industries are performing various strategies in order to reduce waste. However, those strategies are somehow lacking in the matter of effectiveness of recycling the critical raw materials.

2 Problem and proposed solution

The disposal of raw materials in the smartphone industry is increasing rapidly. The materials are not only filling the environment but also exported to the developing countries through used smartphones which restricts the supply of these materials from secondary production [27].Despite having great technology to European companies, companies are reluctant to integrate the technologies into the recycling processes which results in a fragile recycling foundation. For example, mobile phone companies were able to recycle 13-14 Percent of the total e-waste in the year of 2008 out of 3.16 Million tons generated [18]. Because of having a low recyclability rate, there is already scarcity of precious metals and materials that are required to produce smartphones. Materials such as indium, platinum, copper and cobalt are already in scarce [21]. It is also found that the exported wastes are handled without protective gear of any kind by the workers of the exported country. As a consequence, it results in exposure to toxic material in the environment [5] [6]. The lack of customer awareness is equally responsible for this low recycling rate [30]. Overall, the company's recycling and regulatory infrastructure are lacking in order to effectively recycle the critical raw materials [13] [25]. To tackle this problem, customer awareness should be increased so that they must follow a closed-loop cycle for their consumed products and return them to the recycling company at the end of the use. In addition, recycling technology must be improved so that there is less necessity of exporting waste to low-income countries. The system dynamics model should help to understand the problem precisely and observe the growth rate more statistically [20] [1]. Needless to say, there are not many studies that have been found which have explained these recycling issues through dynamic modeling.

2.1 Research and sub-research questions

The problem could lead to the following research question: "To what extent does increasing customer awareness and improved recycling processes contribute to the production of critical raw materials?" In order to answer the research question, some sub-questions can be added:
1. What characteristics do the critical raw materials have that make the European economy unstable?
2. What are the real challenges for recycling the critical raw materials from the EOL and EOU products?
3. What is the relationship between customer awareness and collection of used products and further investigating the recycling process for the used products?
4. Are there any alternative materials or alternative CRMs that can substitute the insufficient CRMs?

3 Methodology

This research is done in a few steps by answering the sub research questions. To answer the first sub-research question, an extensive literature study has conducted about the characteristics of important critical raw materials such as cobalt, indium, lithium, magnesium, and gallium and the real challenges of recycling them [4]. In addition, the customer's attitude regarding their used mobile phones also influences the production of the critical raw material miserably from recycling. The real challenges of recycling as well as the consumer's attitude are handled in the second sub-research question.
The third research question will be observed in two stages and to answer this question a system dynamic tool called insight maker will be used. In the first stage, A stock and flow diagram has created for the collection of used products. Later, the changes in the collection amount will be compared. In the second stage, the primary and secondary production of Indium is compared through dynamic modeling. Both comparisons should help the company to make decisions about its recycling structure.
Nevertheless, there are some parts or certain amounts of valuable metals that can not be extracted even by executing the advanced recycling techniques [5] [20]. This matter will be managed by answering the fourth sub-research question. In order to find some alternatives, the literature search technique is used again for gathering some information such as finding the materials which are cheap, flexible, non-toxic and can sever the same purpose as CRMs.

4 Characteristics of CRMs and Company's focus

In Europe, the different manufacturers consume more than one-fourth of the world's raw materials but they can only produce three percent of those [26]. Therefore, European countries are extremely dependent on the imports of materials and metals. The imports are not always pleasant in the sense of economically, strategically and environmentally. Among those materials and metals, some materials have a high risk with their supply and are very important for the European economy. By taking into account the materials supply issues and economic value, the European commission listed some raw materials as CRMs for the first time in 2011 according to their criticality. At the very latest, the commission has announced a list of 27 raw materials as CRMs including Cobalt, Indium, Lithium, Magnesium, Gallium [10]. There are a few assessment criteria in order to evaluate the criticality of those materials. The most influential are supply risk, economical implications, vulnerability and environmental implications [14]. Supply risk has great significance for the purpose of this paper since it also includes the supply of recycled raw materials.

Supply risk of a critical raw material refers to the risk of a disturbance in the EU supply chain of the materials. Various mobile production company uses almost 58 different materials including the specified CRMs [17]. Table1 shows the top five critical raw materials used in mobile phones. All of those materials are not easily obtainable. The company has to import a huge amount of metals and materials from outside Europe in order to manufacture a mobile phone. While importing those materials, there are always some risks including there are naturally sufficient amounts of materials to meet the demand, the feasibility of obtaining those materials and the economic value. The supply risk can consist of three factors.
The first factor is the geological issue. It expresses the availability of CRMs in the environment. In consideration of different industries such as the mobile phone industry, and automotive industry consuming the same materials for production, they also need to make sure there is enough availability of those materials. Table 1 also shows the use of CRMs in different industries. The European Commission has reported a statistic about three CRMs named Gallium, Germanium and Indium that are used in almost all industries across all supply chain stages. This statistic showed that from 1973-2013, the production of Gallium and Indium increased by 2075 and 1377 percent but the production of Germanium increased only 107 percent[11]. After realizing the necessity of materials, some of their production has certainly increased but few of the rare materials are still in shortage.
The second factor is technological issues that should refer to the certain extent of the materials that can be obtained. It has been found that the countries which have an abundance of rare and critical materials do not always have the proper technological support, resources and infrastructure for extracting the materials[27]. The European green deal[31]reports that the European company perhaps can include the extraction and recycling procedures that are completed outside Europe under the production process of a product. By doing so, they can assist the supplying country by providing feasible technology and resources. This rule also applies to handling e-waste as well.
The last factor is the economic value of obtaining the materials. Even though there is the availability of certain materials in the environment, it is not always pleasant to collect them. Some obvious costs such as the financial cost of production, the medical cost of the labor, opportunity cost and illiteracy cost should be taken into account before extracting and recovering the materials[27]. Some companies failed to meet the expected budget which results in less extraction of those rare and critical materials. Therefore, the main concern is the reason behind existing such supply risks in the European market. It has been found that none of the European countries are producing any of the five specified materials. Thus, it is obvious the countries do not have any reservations 0f those materials either. In this case, they are becoming more vulnerable by importing a great amount of materials every year. Table1 gives an overview of this information. Table 1 gives an overview of these information.

So far, it has been comprehensive that production in the first-hand is one of the most important supply sources of the CRMs. However, by taking into account the need for materials for the world's growing population, the European Green Deal [31] has proposed to evolve the recycling strategy and it could be proved as a major pillar of raw materials supply in near future. According to the document, every company should focus on recycling of critical raw materials rather than relying on importing. The initial plan is to extract as much material as possible by recycling and then import the rest for future production. Recycling is very important in the recent production perspective. It could help minimize carbon footprints. The company can now focus less on producing and harvesting the materials since a big portion of those materials can be supplied by recycling. It also results in saving energy, and less pollution and fewer

Table 1: Analysis of top five critical raw materials(A big portion of data has been collected from USGS website)

CRMs	**Using**	**Advantages**	**Reserved (tons)**	**Abundance in country**	**Used in Different industry**
Cobalt	Rechargeable batteries, circuits and microchips	Allow high energy density, Capable of storing a lot of energy in a small metal.	7.6 Million tons reserved. The estimated refinery production of 2021 is 1,70,000 tons.	Congo(70%)	Aerospace, Medical, Mobile phone
Indium	LCD Display, Touch screen device, Mobile phone display	It is so transparent and electrically conductive making the touch screen more stable.	Quantitative estimation is not available, but the estimated refinery production of 2021 is 920 tons.	China (57%), South Korea (21%)	Mobile phones, Photovoltaic solar cells.
Magnesium	Framing and casing	Low weight and making electronics more resilient.	Quantitative estimation is not available. But the estimated refinery production of 2021 is 950 tons.	China (66%)	Automotive, mobile phone, luggage, Television.
Gallium	Used in LEDs as camera light.	Can transport energy faster than its competitors.	Quantitative estimation is not available. But the estimated refinery production of 2021 is 4,30,000 tons.	China (82%)	Pharmaceuticals, Mobile phone, Nuclear medicine test.
Lithium	Cathodes production in Lithium-ion batteries.	Lithium ion batteries always keep the voltage fixed, no matter how much energy has been consumed, and it's very easy to maintain	2,20,000,00 tons reserved.$\sim$The estimated refinery production of 2021 is 10,0000 tons.	Australia (46.3%), Chile (29.3%), China (16.2%)	Glasses, Pharmaceuticals, Mobile phones.

greenhouse gasses[7]. Recycling critical raw materials is also not as smooth as it sounds. There are some real challenges that have to be taken into account for materials recycling.

5 The real challenges for recycling

It is beyond saying that the majority of the CRMs supply comes from extraction and refinery mechanisms. Extracting and refining them cost a huge amount of money and hard labor. At the time of exporting the e-waste to the recycling country, the wastes have to travel a long distance. The more the materials and wastes travel, the more carbon emits into the environment [20]. When the amount of carbon emission is increased in the environment, it has a negative impact on the sustainable world. In this case, the companies need to focus more on recycling. If every company empowers recycling technology more efficiently, they can acquire a great number of materials from the used product [30]. By doing so, the company needs to focus less on the production of CRMs, importing the insufficient CRMs and exporting the e-waste. In the next section, the real challenges of recovering CRMs are discussed.

5.1 The four factors and recommendations according to European Policy

There are four factors in force for having such a low rate in recycling. The first factor would be the collection of used products. Research has reported that insufficient collection of EOL and EOU products is one of the main incentives for low recycling [13][2]. The European Policy [31] proposed to follow a product as a service model where the company keeps the ownership of a mobile phone and are responsible for the performance and service for the whole life cycle of the product. It could strengthen the closed-loop supply chain and makes sure that not a single phone has been dumped or showcased in the drawer. If possible, every company must introduce a scheme or system where the customer can sell or return the old phones with benefits.

The second factor would be not having or following proper policy and legislation for practicing e-waste recycling. The European Union [31] provides some rules and regulations associated with the recycling of critical and rare earth materials every two years. These policies should be enforced by the companies for the sake of a sustainable world. One of the common policies that the EU commission has introduced is to integrate only USB-C chargers for all their smartphones so that people can reuse their chargers and meaning less waste in the environment.

The third factor would be the lack of integration between the advanced technology and the recycling and recovering processes. European company has a great tendency to export waste so that they can focus more on product production rather than recycling. It results that the companies' in-house recycling infrastructure is not advanced. The European Policy always recommends having a good technological foundation such as a specific department for scrap collection and separation, advanced machines for sputtering and assembly process and heating mechanism for commissioning and decommissioning to the manufacturers[15]. The companies can also focus more on the extensive use of recycled content in the product. In this way, they would never hang for the supply of the materials.

The last factor is very common and is the illegal export of dangerous wastes to the developing countries that could act as a slow poison for those countries and could pose a serious risk to the human body and their environment. According to the European Commissions' report, if a company has been caught illegally exporting more than the approved amount of the wastes, the company will be taken into the court and the court will impose penalties according to the infringement [31].

5.2 Collection of EOL and EOU products

The company sometimes fails dreadfully to provide and introduce a closed-loop supply chain where the reverse logistic has been forced. It results in a low collection rate and high landfill rate of a product. The landfill rate refers to the rate of a certain amount of used product on the land. In this section, the companies' actions and the collection of EOL and EOU products will be analyzed. The relation between these two parameters and what makes increasing the collection used product will be discussed analytically.

5.2.1 Method

In this research a system dynamic tool called insight maker is used in order to analyze the collection of used products. From the number of used products, the percentage of recycled materials can be extracted. A flow has been created which can be found in Figure 1. The collection is the main stock in this flow. There is one inflow called used product and two outflows called landfill and recycled product in this diagram. The dynamic behavior of this diagram has been calculated by a set of equations inside the insight maker. The behavior of the stock namely collection has been determined by the difference between inflows and outflows.

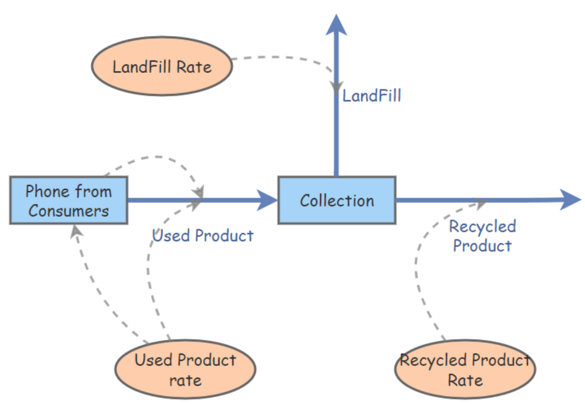

Figure 1: Stock and flow diagram of Collection

5.2.2 Data collection

In order to know about the collection of EOL and EOU products, a lot of literature has been studied. The main concern was here about having a low collection rate. Three of mentioned four factors are all related to the companies' behavior and the government's policy-making. Furthermore, They are taking necessary steps to overcome the problems related to recycling. However, when it comes to the collection of products, the consumer has a direct influence on this factor. It has been found that only 50 percent of the used product can be collected every year [22]. From those collections, around 8 percent of the waste goes to the environment. This includes two scenarios. The first scenario is that the used product can be dumped by the consumer themselves without taking them to the recycle center and the second scenario is when sorting the waste, there are some components that cannot be recycled, and therefore go to the environment for dumping. On average 12.5 percent of e-wastes recycle every year [29]. The second statistic has been collected from the European Commission website. These data are used in order to simulate the different situation of the collection stock. The expectation is that if the consumers decide to return the old phones to the recycle center rather than keeping them in the drawer or dumping them with the normal waste. The collection rate will increase and the landfill rate will decrease in great portion. It can have a positive impact on recycling as well.

5.2.3 Results

Two different situations have been taken into account. One is analyzing the scenario with the current data that is given and another one is manipulating the existing data by assuming that consumers are now motivated and have the batter opportunity to return their old used phones. Figure 2 shows the current stock and the improved stock of the collection of used phones. For the current situation, 50 percent of used products rate has been taken into account For the improved situation, 60 percent of used products rate has been taken into account. At the same time, the landfill rate was 8 percent, and 5 percent respectively. Ten years of time limit has been considered in this case.

From the Figure 3, a statistical growth of collection stock can be noticed more precisely.

5.2.4 Discussions

According to the results, it has been proved that a 10 percent increase in collection rate could make a significant difference in the collection stock. Therefore, it's high time the mobile phone selling company promoted their return policy robustly. They can introduce a point collection or reward collection process for those phones which will be returned at the end of their uses. From the result, it is also noticeable that the improved situation can increase the collection stock up to 3322.09 metric tons for the next ten years and an average of 332 metric tons per year. One more interesting finding from this simulation is that the collection amount has a positive impact on the recycling rate. By collecting more products, the company can make sure the CRMs are recovered carefully from the products. Figure 4 shows the difference in current recycled products and with improved situation's recycled products. A sharp 46.1 percent increase in recycled products has been witnessed in this simulation.

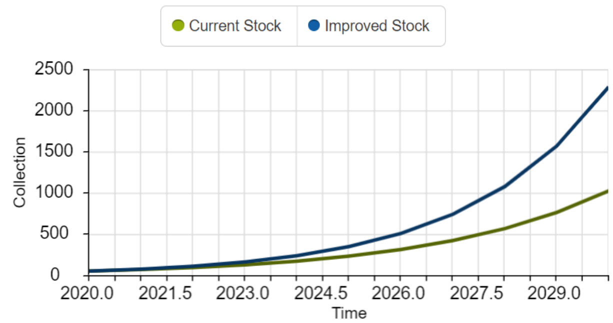

Figure 2: Current and improved collection stock

Time(Year)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Current Stock	53.7	72.12483	96.87135	130.1086	174.7497	234.7075	315.2373	423.3973	568.6678	763.7816	1025.84
Improved Stock	53.7	78.1295	113.6726	165.3852	240.6231	350.0887	509.353	741.0707	1078.203	1568.705	2282.348

Figure 3: Current and improved collection table

6 Investing recycling strategy for critical raw material (Indium)

Due to the overwhelming demand for highly technical devices, the consumption of critical raw materials is increasing day by day. It has already been mentioned that specified CRMs are part and parcel of manufacturing mobile phones. Though the majority supply of the CRMs comes from production, extraction through recycling could also never be unnoticed. Research has also shown that an improved recycling strategy should add an extra level to a greener world and change the economical infrastructure

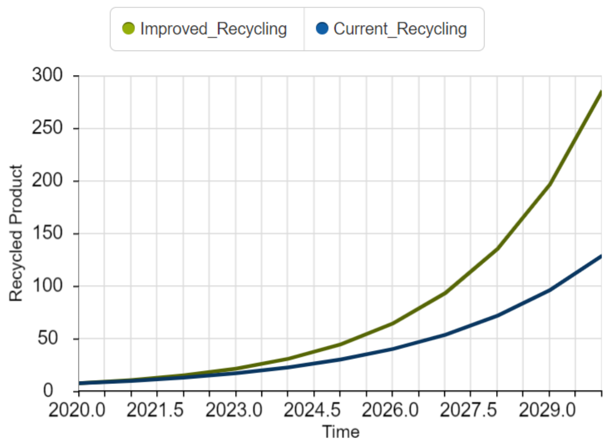

Figure 4: Current and improved recycled product stock

of a company [18][28]. Extracting CRMs from the environment is known as primary production and acquiring CRMs through recycling would be secondary production. In this section, the secondary production of Indium will be discussed and analyzed through the system dynamic tool. It will be reported that improving technological processes should increase this secondary production of indium[32]. Indium has been chosen in this case because the real time data cannot be extracted for other CRMs. The objectives of the analysis are-

- Primary production situation will be taken into account for understanding the current situation.
- A extended stock and flow diagram will be made for the indium recycling strategy in order to compare it with the current situation.
- Analyzing the increment of the indium stock.

6.1 Method

A stock and flow diagram has been made in the insight maker. This is an extended diagram with the collection and recycling processes on it. It can be found in figure 5. The model has six different stocks including indium stock, ITO production, IT products, Consumed products, Sorting, Separation. Every stock is linked with their respective variables. Variables are basically the percentages. The differences between inflows and outflows are calculated inside different stocks. This model also represents the closed-loop supply chain of indium.

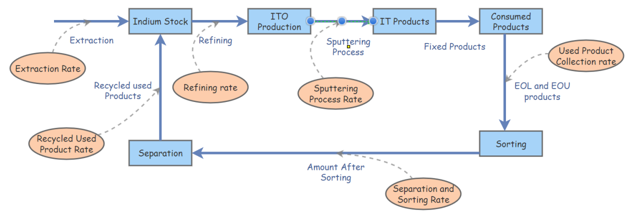

Figure 5: Stock and flow diagram of indium

6.2 Data collection

Data has been collected from various literature, journal and website. At some point, it was troublesome to find real-time data for some variables. To resolve this problem, the average of the last five years' data has been calculated. As of data, 90 percent of indium can be extracted naturally and the re-fining rate of the extracted indium is 70 percent which is used in ITO production[33]. For the sputtering process of ITO production, 84 percent of indium is used[8].An average of 30.4 percent of indium can be collected from used products[24]. The sorting and separating rate of indium-based mobile phone are calculated by the average. 1000 kg of indium can be separated per hour from recyclable products. Therefore, 55 metric tonnes can be separated by a percentage of 50[12]. Recycling indium from the EOL and EOU is very low because of their low concentration inside the product. Thus, a 20 percent recycling rate has been considered in this case [8]. In the model, all of the stocks are parameters, since they are not subjective to change and rather constant. And these parameters behave differently according to the variables that are assigned. In Appendix, Table A1 shows the overview of parameters and variables.

6.3 Results

Yet again, two different situations have been taken into account. One is with the current scenario and more specifically reflects the primary production of Indium from the environment. This scenario is displayed in Figure 6 Another scenario is adding the secondary production processes of indium to the model. This secondary production includes the improved recycling strategy. This scenario is displayed in Figure 7. In the end, it has been found a significant amount of increase in indium stock while applying improved recycling methods.

From Figure 8, the growth of Indium stock after applying improved recycling technology can noticed more precisely.

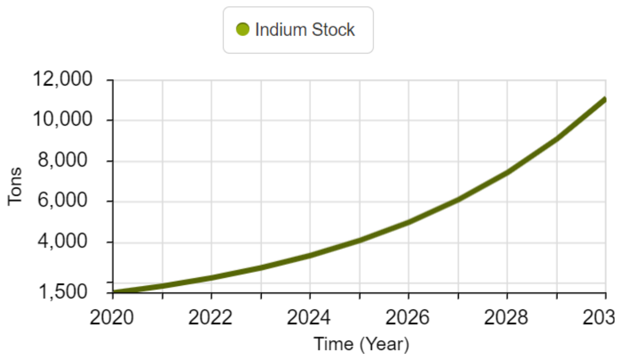

Figure 6: Current Situation of Indium Stock

Figure 7: Improved Situation of Indium Stock

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Current Situation	1500	1832.1	2237.727	2733.16	3338.281	4077.377	4980.108	6082.704	7429.414	9074.287	11083.33
Improved Situation	1500	1894.022	2418.065	3116.636	4046.766	5278.639	6899.971	9022.8	11792.3	15397.88	20087.22

Figure 8: Current and Improved Situation of Indium Stock

6.4 Discussions

From the result, it can be concluded that the simulation of the second scenario reports a remarkable increase in indium stock. Therefore, the companies should strengthen their recycling infrastructure rather than export e-waste. From the Figure 8, it can be stated that having the improved recycling process and reverse logistics methods of the closed-loop supply chain, indium stock can have a 33.2 percent increase in the next ten years. An average of 8145 metric tons of indium can be produced per year.

7 Alternative materials for CRMs

There has always been a possibility that recycling does not go perfectly by taking into account the company's resources and scope. It recurrently results in relying on the production and importing of materials from outside of Europe. Therefore, the necessity of finding alternatives is in force not only for having a low recycling rate of those CRMs but also their demand has been increasing tremendously. A research has shown that the demand for Gallium will have increased 300 percent by the year 2030 [19]. Increasing demand has a bad impact on the supply chain unless the supply and recycling do not meet the expected threshold. In this section, some substitutes will be discussed for the specified critical raw materials. Finding alternative for indium is not feasible because of extensive use of this material.

7.1 Replacement of Cobalt

The use of cobalt in the electronics device has been mentioned in table 1. The main use of cobalt is in the lithium-ion batteries in the mobile phone. The battery has two electrode components named anode and cathode. Cobalt is found in this positive cathode. The use of the cobalt in the cathode makes the process smooth by passing the electron to the external circuit of the mobile which makes the phones run. The use of Lithium-ion batteries has been increasing rapidly because of their high energy storing capability. Therefore, the demand for cobalt is also increasing. It is always wise to think about alternatives that could replace this high demand in future. Cobalt has a replacement named manganese[9]. The characteristics and use are practically the same when using them on a mobile phone.In Appendix, Table A2 shows the comparison between the cobalt and its probable alternative Manganese.

7.2 Replacement of Indium

Indium is used in highly technical devices such as mobile phone's display and different kinds of touch screen gadgets. The composition of indium and Oxygen named Indium tin oxide is the most used scenario in this case. Thus, while using Indium in the display, the manufacturer needs to take into account the storing of ITO as materials. A touch screen is required to be electrically conductive and transparent. And the electrical conductivity of this ITO composition is very high and it's optically transparent. However, there is always a risk underlying the supply of indium since the mining of Indium depends on the mining of zinc. Therefore, a replacement of indium can be forced in practice. Research has shown that graphene could be a good substitution of indium[3]. In Appendix, TableA3 shows the comparison between the indium and its probable substitution graphene.

7.3 Replacement of Lithium

Despite having a huge mining related cost, constrained supply chain and limited recycling infrastructure, lithium is the most used material in any kind of batteries. The reason is that it has high energy density, capability to keep the voltage fixed according to the power and a lingering life cycle as most of the parts are recyclable. Lithium is used as a form of lithium ion in the mobile phone's battery and it's called Li-ion battery. Because of an unstable supply chain and restricted recycling infrastructure, scientists are searching for replacements of Li-ion based batteries. The Zinc based batteries could be an ultimate substitution of Li-ion batteries[23]. In this case, a composition of Zinc and Nickel called Nickel 3D Zinc based alkaline batteries can be used in mobile phones. In Appendix, TableA4 shows the comparison between the lithium and its probable substitution Zinc.

7.4 Replacement of Gallium

Gallium is used in the form of gallium arsenide (GaAs) in mobile phones. GaAs has the capability to convert the electricity to light and further this light is used in light emitting diodes (LEDs), amplifiers and transistors. One more important point is that the use of Gallium metal in the device keeps it cool by transporting the electrons faster. However, acquiring gallium is certainly a problem for having limited supply and mining costing. A suitable substitution of gallium would be Silicon based metal[16]. This silicon based metal-oxide semiconductor can be used in amplifiers that more likely to compete with gallium arsenide semiconductors in the future. The characteristic would be almost similar for both semiconductors which could be further re-searchable. In Appendix, TableA5 shows the comparison between the gallium and its probable substitution Silicon.

8 Conclusion

In order to answer the question of whether increasing consumer awareness and improved recycling processes contribute effectively to the production of critical raw materials, a system dynamic modeling tool was used. The purposes of the model are to investigate different conditions of customer behavior according to their old used phones and the statistical growth between primary and secondary production of critical raw material. Both the purposes are simulated in two scenarios. In the first scenario, the current situation is displayed which required some real-time data. It was very challenging to find them from the literature and the website. In the second scenario, an improved situation is reported and it was done by either manipulating the data or extending the model with multiple processes.

When the data was collected in order to observe customer behavior, it was realized that most companies focus less on the matter of critical raw materials future. This information helps to answer the first sub-research question. From the analysis, because of having a very critical supply chain and less availability throughout Europe, finding alternatives way of CRMs production should be prioritized for the mobile phone industry. It will stable the European economy.

The alternative way of production is apparently the secondary production of CRMs. This secondary production includes the whole recycling process in the background. This situation leads to answering the second sub-research question. It has been found that the recycling processes also come with great challenges. the recycling rate of CRMs is very low. Some factors are responsible for having such a low rate. Among them the low collection of used products and weaken recycling process are most concerned. By properly following the policy and legislation and strengthening the reverse logistic methods, these challenges can be overcome.

After analyzing the third sub-research question, it can be stated that customer behavior has a great influence on the collection of EOL and EOU products. Once the consumer starts bringing their old and unused phones to the recycle center, the extraction rate of very precious and critical material will be increased from the e-waste. It is also found that the company should more focus on the improvement of their recycling infrastructure. In this way, they will not only depend on the primary production of the CRMs. A great portion of CRMs can be achieved by recovering used phones as well. From the simulation, significant growth of indium stock has been recorded with the improved recovering process.

The model only predicts the production of CRMs for the next ten years. But the important concern is the scope and situation can be changed in the future which might hinder both the primary and secondary production of those CRMs. The importance of the last research question is in force in this situation. This paper also suggests some alternatives that could substitute the above-mentioned CRMs in near future. Invoking the use of alternatives should release the strain on CRMs supply.
There are some limitations in this paper that could be improved in future research. The first constraint of these limitations would be that this paper only made a prediction for indium stock because data was found easily from reliable sources. In this short period of project time, it was very difficult to find the necessary data to run a simulation model for all the CRMs. In the future, a lot more literature studies and expert interviews can be done in order to collect data. The second constraint would be choosing most of the data from 2020's statistics. It was very difficult to find data from 2021 or 2022. It might be a reason that the latest data was not updated after the corona epidemic. The third constraint would be choosing the alternatives for the critical materials. The economic and environmental perspectives were the main incentives for choosing the alternatives in this case. However, the incentive criteria such as the characteristics can be expanded in the following research.

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Appendix

Table A1: The parameters and variables of indium recycling model

Parameter	Value	Variable	Percentage	Source
Indium Stock	1500	Extraction Rate	0.90	[33]
ITO Production	1500	Refining Rate	0.70	[33]
IT Products	1000	Sputtering Process Rate	0.84	[8]
Consumed Products	800	Used Product Collection Rate	0.304	[24]
Sorting	400	Separation and Sorting Rate	0.50	[12]
Separation	200	Recycled Used Product Rate	0.20	[8]

Table A2: Cobalt(CRM) vs Manganese(Substitutor)

Materials	Cobalt	Manganese
Use	Rechargeable Batteries, Lithium-ion batteries.	Circuits, dry cell battery. It can make the mobile phone more resilient.
Price	Expensive. $40,000 per ton.	Cheap. $1,700 per ton.
Toxicity	Very toxic material. It can be very harmful to eyes, lungs and skin.	Comparatively less toxic. It can still cause neurological disorders at the presence of too high concentration.
Oxidization	Easily oxidized	Easily oxidized
Mining Practice	Cobalt could be mined unethically. Child labor and dangerous working condition has been reported in the mining area.	It can be found all over the world therefore mining process should be stable and inexpensive.

Table A3: Indium(CRM) vs Graphene(Substitutor)

Materials	**Indium**	**Graphene**
Use	LCD Display, Touch screen device, Mobile phone display.	Any kind of touch screen smart device, used in mobile phone's battery for increasing efficiency and stability.
Price	Expensive $1,95,839 per ton	Cheaper than Indium $90,700 per ton
Toxicity	Relatively nontoxic material, poses less harm to the health. Excessive absorption of ITO could be harmful to the lungs and immune system.	Relatively non toxic material. Liver and kidney injury is reported in exceptional cases.
Oxidization	Indium tin oxide is the most used composition in the mobile phone	Graphene oxide is the most used composition in the mobile phone.
Mining Practice	Can be found as a by-product of zinc and lead mining. Thus, the extraction and expenses of mining all are related to zinc and lead mining.	Graphene is an atom of carbon. Carbon can be found everywhere in the world. So, mining carbon and preparing graphene shouldn't be very difficult and costly.

Table A4: Lithium(CRM) vs Zinc(Substitutor)

Materials	**Lithium**	**Zinc**
Use	Cathodes production in Lithium-ion batteries.	Mostly used in mobile phone circuit boards. Can be used in a mixture with a low percentage of Nickel and formed Nickel 3D Zinc-based batteries.
Price	Expensive $46,460 per ton	Cheap $3,856 per ton
Toxicity	It's a toxic material. 15 mg of lithium in the blood can cause death. It's been recommended that the intake should be lower than 14 microg.	It's a nontoxic material.
Advantages	Lithium has one electron to redox, therefore the Li-ion battery can hold more capacity and power in its shell.	Zinc has two electrons to redox which can be removed easily and deliberately have high capacity and power like Lithium.
Mining Practice	Lithium is widely available and it is not a big problem to find them. However, mining lithium needs a huge amount of water to be used which could have a bad impact on the environment.	Zinc can also be found throughout the world and it can be found in the form of zinc oxide and zinc sulfide. One more advantage of mining zinc is that lead, silver and indium can also be extracted as by-products of zinc mining.

Table A5: Gallium(CRM) vs Silicon(Substitutor)

Materials /Criteria	**Gallium**	**Silicon**
Use	Used in LEDs, amplifiers, transistors and mobile phone chargers.	Semiconductors that are made of silicon can act like an insulator that can conduct electricity.
Price	Expensive $4,49,872 per tons	Very Cheap $2,644 per ton
Toxicity	It's relatively non-toxic. But ingestion of gallium could be harmful.	Silicon can be found in its natural form from the environment. So, it's a completely nontoxic material.
Composition	Gallium arsenide(GaAs) and Gallium Nitride(GaN) can be used.	Silicon based metal-oxide can be used.
Mining Practice	It can hardly be found as an individual element from nature. Therefore most gallium can be found as a by-product of zinc and aluminum mining.	It can be found in the sand. Sand is abundant in the world. So, acquiring silicon is one of the easiest jobs.