A simulation of the ecological impact of three smartphone strategies

Frans Schooltink
University of Twente
PO Box 217, 7500 AE Enschede
the Netherlands

f.a.e.schooltink@student.utwente.nl

ABSTRACT

Smartphone technology has seen an exponential boom in popularity and complexity ever since the release of the original iPhone in the late 2000s. New smartphone models are coming out every year. In first-world countries, smartphones are usually replaced after 2.5 years of operation even if the phone is still functional [28]. This rate of replacement has led experts to sound the alarm bell in hopes of lessening the smartphones industry's ecological impact.

Smartphone companies are adjusting their business strategies to be more environmentally friendly. Some information exists on the effectiveness of some of these strategies but thus far there is a lack of comparisons, and the effectiveness of alternate strategies has not yet been tested. To fill this void this paper aims to examine and compare the effectiveness of three smartphone strategies: production process refinement, modular technology, and refurbishment.

Three steps were performed to find the best strategy. First, a quantitative literature review was conducted to determine the aspects of each of the three strategies. Information on emissions, amount of waste, and lifespan was collected. This data was then used to construct a simulational ecological impact model. The results of this model in combination with the information collected during the literature review were then used to determine the most effective strategy.

It was estimated using the ecological impact model that at a 5% deployment of strategies a refurbishment strategy, with 36.7 kg of CO2 per and 131.308 g of e-waste per smartphone, is the most effective strategy at reducing ecological impact. This would mean a 4.7% reduction in emissions and a 4.8% reduction in e-waste.

The refurbishment strategy also has major downsides. Recycling still requires regular models to be purchased. It also requires these old regular smartphones to meet a certain quality standard to be eligible for refurbishment. Another problem is that western consumer markets currently show very little interest in refurbishing[30].

Keywords

E-waste, smartphones, refurbishing, modular technology, recycling, circular economy, Life Cycle Assessment, business strategy, modeling, sustainability

1. INTRODUCTION

Smartphones have become an integral part of human lives in western society. Since the release of the iPhone in 2007 smartphones became bigger, faster, and better and the market has grown into a 500 billion dollar industry in 2018 [25]. While this tremendous growth has exciting implications for how our future society might communicate, people tend to overlook the environmental impact these technologies have. A study commissioned by the United Nations conducted by Forti et al. in 2020[17] showed that 53.6 million tons of electronic waste, e-waste, were generated in 2019. The subsection small IT and telecommunication equipment of waste to which smartphones belong makes up 4.7 million tons, 8.8 percent of total waste. This is an increase of 0.8 million tons since 2016[10]. The amount of E-waste smartphones represent might be misleading as most smartphones are never disposed of but instead remain dormant in people's homes[28].

While the current and future ecological impact of smartphones has already been examined in papers like Bridgens et al.[11] and Belkir et al.[20] these papers only consider the current state of the industry. Rizos et al.[23] does highlight the possible viability of different business strategies, however, their paper does not reflect on the effectiveness of these strategies. This paper, therefore, aims to supplement these initial works by providing science-based evidence that alternate business strategies might be the key to lessening the environmental impact of smartphones. This was done by designing an Agent-Based Ecological Impact Model to compare three different business strategies.

The three business strategies examined in this paper are Production Process Streamlining, Modular Smartphone Technology, and Refurbishment.

The strategy of designing smartphones to be modular involves designing smartphone components to be easily replaced. This increases the lifespan and therefore combats the high replacement rate of smartphones. To examine the effectiveness of this strategy data of the modular Fairphone 2 and 3 was used.

Refurbishing is the business strategy of collecting old phones and making them "as new". This means replacing old or broken parts and updating software. These refurbished phones can then be resold for a second life. Currently, this strategy lacks in popularity[29].

The final strategy, Production Process Refinement, entails the optimization of smartphone production. This is a viable strategy because more than 60% of emissions are generated during production[12]. The production costs are so high because Integrated Circuits have some of the highest environmental impacts per mass unit[14]. Smartphones have a very fast replacement rate for a relatively costly product to produce[20].

The Ecological Impact Model was constructed by first conducting a literature review to collect detailed information on each of the three business strategies.

The data retrieved from this literature review was then used to create the model. The model generates a static population of smartphones according to the parameters provided. The model allows for examination of the effectiveness of full or partial deployment of each of the three business strategies.

Combining both the data from the literature review and the model, conclusions as to the effectiveness of each strategy can be drawn. According to the data gathered, Production Process Streamlining won't be enough to decrease the growth in emissions and waste per phone unless markable technological changes occur in the production process. The alternative business strategies seem more effective at reducing emissions but both have disadvantages. Adopting Modular Smartphone Technology would mean a slight increase in e-waste produced per phone due to the bulkier design of the smartphone and its components. Adopting more widespread Refurbishing would reduce both emissions and waste, however, this requires the purchase of new models. While consumers in current western society seem unwilling to purchase second-hand phones[29], a market for such goods may be found in non-western markets, where the lower cost of refurbished devices might be more attractive due to lower personal wealth.

This paper gives smartphone companies, climate change legislators, climate activists, and other people with an interest in reducing the carbon footprint of the smartphone industry or similar electronic industries a summary and comparison of three potentially viable business strategies that could help reduce climate change. The model used in this paper can also be used to examine the effectiveness of the strategies should different parameters be chosen than the values found during the literature review.

2. PROBLEM STATEMENT

To create a model to examine the effectiveness of the three chosen strategies grounds for comparison had to be drawn. To find these parameters, first, a phase of quantitative literature review was conducted.

Keywords that were used are: “refurbishing”, “recycling”, “Modular Technology”, “smartphones”, “Circular Economy”, “Circular Technology”, “e-waste”, “Life Cycle Assessment” and “business strategy”. These keywords were then combined on Scopus and Web of Science to find initial articles. Reference Search was used to find more articles related to the subject.

Table 1: Chosen assessment parameters of business strategies

Parameters
The average lifespan per smartphone
The amount of CO2 emissions in kilograms
The amount of electronic waste produced per device in grams
Socio-Political or Technical circumstances affecting effectivity.

To direct the literature review and the construction of the model the following Research Question was drawn up.

Which of the three business strategies is the most effective at reducing the environmental impact of the smartphone industry?

To further focus the research the following subquestions were drawn up.

1. What are the leading parameters that determine the effectiveness of each business strategy?
2. How can these parameters be used to create a model that can aid in determining the effectiveness of these business strategies?

3. METHOD OF RESEARCH

This research is conducted in three stages. The first stage consists of expanding on the initial quantitative literature review by finding data on the determined parameters. Because this literature review expands on the literature review conducted in Section 2 the same keywords and search methods were used.

In the literature review, many references to Life Cycle Assessment reports (LCA) are made. Life Cycle Assessments are cradle-to-grave examinations of the ecological impact of a device. These reports are commissioned by smartphone companies and released as promotional material. The LCAs were taken from the smartphone companies Apple, Fairphone, and Huawei. The math of the impact model is based on data retrieved from these LCA reports.

At the time of writing, little information on the actual effectiveness of the refurbishment business strategy is available. However, multiple papers highlighted the possible advantages and disadvantages this strategy might have. To confirm assumptions about the availability of data an email exchange was had with Dr. Kees Baldé.

The second stage is designing the model to compare the three business strategies. For the creation of this model Netlogo, a java-based agent modeling program was used. Design decisions can be found in paragraph 4. The decision to use Agent-Based Modelling instead of, for example, System Dynamics was made because Agent-Based systems allow for modeling individual behavior. This is ideal for modeling something as volatile as mobile phone lifecycles. While the benefits of this have not been fully utilized in the current version of the model, a future implementation could include things like random breakage or additional modeling of the dropping perceived value of the devices.

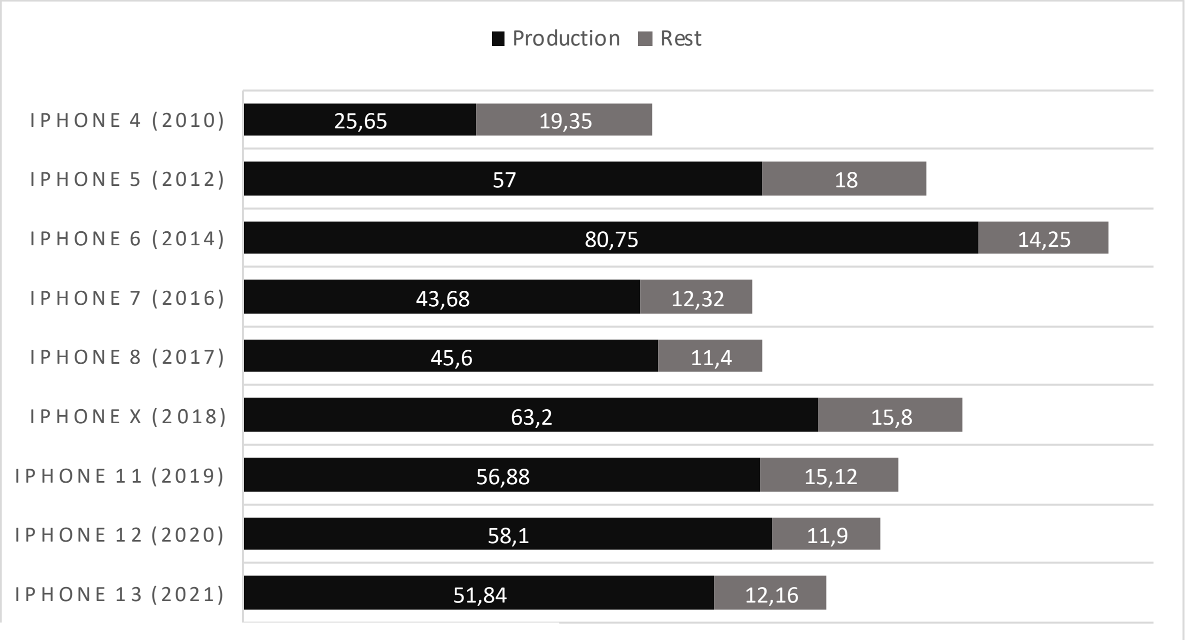
The final stage of research consists of running the simulation with different scenarios for each of the business strategies. The results of these different scenarios can be found in section 6. To assess the effectiveness of each strategy two different scenarios were run. The effectiveness of the modular and refurbished strategies was tested at 5% and 100%.

The strategies were tested at 5% because, as discussed in the literature review the market share of refurbished and modular phones is currently very small and refurbishment has the disadvantage that it relies on models being exchanged. This 5% market share is a value chosen at random but represents the market share of one market-competitive smartphone company applying the strategy[26].

The results were retrieved by running each possible business strategy ten times and taking the average of the resulting values. The number of active smartphone users for these simulations was set at 100 and the number of months to run was set at 240, 20 years.

The results from these simulations were then used to calculate how much the regular smartphone industry would have to reduce its CO2 emissions and e-waste to be just as environmentally friendly as the other two strategies.

By first dividing the amount of CO2 emissions and e-waste produced by the alternate strategy by the average amount of regular phones it can be calculated how much emissions and e-waste a regular phone would have to produce to be just as efficient as the strategy. The average amount of regular phones is based on a base case simulation assuming 100% deployment of standard smartphones without refurbishment. The average amount of regular smartphones found during this simulation was 758.2. By then subtracting these calculated averages from the average CO2 emissions and e-waste of regular phones the difference can be found.



Graph 1: CO2 emissions in kg of iPhone , divided in production and use, transport, packaging, and recycling [1-9]

4. LITERATURE REVIEW

The following literature review contains three subcategories for each of the three business strategies.

4.1 Production Process Streamlining

Production Process Streamlining is a key value in some of the current smartphone company business strategies. Apple promotes its efforts to reduce the Carbon Footprint of its products. To broadcast these efforts they have publicized information about the ecological impact of their products in the form of Life Cycle Assessments. With this information, an overview of the environmental innovation of Apple was made. The timeline starts in 2010 with the iPhone 4 and concludes with the release of the iPhone 13 (2021). Information that was collected from the LCA's was the amount of CO2 produced and the innovation and developments made between each generation.

In 2010 Apple released the iPhone 4, which had the lowest emissions of all iPhones examined. The LCA noted no environmental impact reducing features[1]. This can be attributed to this being the first LCA released by Apple, therefore there was no basis for comparison with the older model phones.

The iPhone 5 (2012) saw a hefty increase in CO2 production due to Apple's decision to incorporate aluminum into their models instead of just using stainless steel[2].

The iPhone 6 (2014) set Apple's record for emission. This increase in emissions can be explained by the iPhone 6 having an increased size, a more complex processor, more storage, and no markable design choices were taken to reduce emissions. While Apple made the claim that their aluminum is highly desired by recyclers [3] it replaces stainless steel a metal that is very easily recycled.

The release of the iPhone 7(2016) marks a turning point in Apple's design, by using aluminum manufactured using hydroelectricity fossil fuel costs were reduced. Another markable change is the inclusion of recycled aluminum during production[4].

The iPhone 8 (2017) saw no markable design changes. Larger CO2 emissions can be contributed to an increase in screen size.

The iPhone X (2018) sees a return to stainless steel instead of aluminum[6]. Apple has not stated why it has returned to using stainless steel. CO2 emissions increased most likely due to an increase in screen size and a more advanced camera.

The release of the iPhone 11 (2019) marks a change of format in Apple's Life Cycle Assessments. Apple has stopped releasing information on the material composition of their phones and no longer note any developments in the environmental design of their smartphones after this generation.

The significant decrease in emissions with the iPhone 13 can most likely be attributed to an improvement to the processor reducing its production costs[7]. The processor and the motherboard are the costliest components to produce[14], so optimizing the production of these components might have large benefits.

In conclusion, the Apple timeline shows periodic high emission cost rises resulting from increases in size, changes of materials, and increases in storage capacity.

Apple was able to reduce the emissions during production in 3 generations of their phones, the highest being the reduction between the iPhone 6 and 7 with 37.07 kgs. It should be noted that the iPhone 6 was also the peak of emissions production. Even though Apple shows that the industry is capable of positive change, the cost of production still seems to be rising with a yearly average of 2.9 kg CO2.

Huawei

The LCA's of three generations of Huawei smartphones were also examined to show that not only Apple suffers from increasing emissions in their production cycle and that Apple is a fair example to examine the trends of the smartphone industry. The Huawei models that were chosen for this study are the Huawei P9 (2016), P30 (2019), and P50 Pro (2021)[18]. These models were chosen for being three generations of the same product line and having similar release dates to iPhone models. The respective iPhone models are the iPhone 7, 11, and 13.

Table 2: CO2 emissions of Huawei models

Model	Total emissions in kg	Production emissions in kg
P9	54.7	46.2
P30	71.7	62.2
P50pro	78	68.5

Table 3: CO2 emission of respective iPhone models

Model	Total emissions in kg	Production emissions in kg
iPhone 7	56	43.68
iPhone 11	72	56.88
iPhone 13	64	51.84

As shown in Tables 2 and 3 the CO2 emissions generated during the production of the Huawei models are higher than those of Apple. This is especially notable seeing as Huawei does not utilize aluminum in their products and therefore should have lower base emissions[18].

The larger emissions in the gate-to-grave part of the lifespan of Apple products might be explained by a longer life expectancy for iPhones. Huawei utilizes a lifespan estimate of 2 years[18] which is low by industry standards while Apple uses an average lifespan of 3 years[27]. This leads to Apple having more CO2 emissions during the use phase of their products.

4.2 Investing in Refurbishment

To refurbish according to the Merriam-Webster dictionary is to brighten or freshen up. Refurbishment is implemented in the mechanical and electronic markets by collecting old devices and giving them a second life[30]. This is done by cleaning and replacing the hardware, and resetting and updating the software.

Consumers in western countries seem to show little interest in refurbished devices. Due to higher personal wealth, they value being trendy and having a completely new device over their dedication to recycling[15]. In the current smartphone market, refurbished phones might instead be better marketed towards non-western countries. This would provide an affordable option to acquire older smartphone models in markets where the availability of smartphones is scarce.

According to Kees Baldé, an expert in the field of e-waste reduction and circular economy, there is no data available on the number of phones that are eligible for refurbishment or how many phones refurbishing companies currently handle. There is an upper limit to how many phones could be refurbished though. A study in the United States showed that currently, only 11% of smartphones end up getting recycled[11].

This business strategy has the disadvantage that it has low economic gain therefore not a lot of investment is made to develop this business strategy[24].

4.3 Modular Cellphone Technology

The strategy of modular cellphone technology involves changing the base standards of the smartphone industry to be more aimed towards repairability and self-repair. A business focused on Modular Technology aims to increase smartphone lifespan by designing and making easily replaceable components such as the battery, camera, and screen available for purchase by the public.

While concepts of modular cellphones have existed since 2013 with the award-winning concept from Dave Hakkens, PhoneBlocks, there are currently only two companies that have successfully released phones with modular components in the European market[23]. These two companies, Fairphone, and Shiftphone provide a first example of what an effective modular cellphone strategy might look like.

Fairphone has released detailed Life Cycle Assessments of both the Fairphone 2[21] and 3[22]. The Fairphone 2 (2015) has an emission cost of 35.98 kg CO2, making its emission similar to its contemporaries the iPhone 7 and the P9. The Fairphone 3 (2019) had 32.2 kg of CO2 making it more efficient than most of the current smartphone market. Fraunhofer IZM has determined that the connectors do not seem to significantly increase the CO2 emissions of the Fairphone they however need gold, thus requiring more precious materials to be used[22]. The LCAs also contain estimations of the emissions produced in further life. Fairphone expects their phones to be kept in use for at least 5 years however Lithium-Ion Batteries last only 3 years on average[13] meaning that a battery replacement is needed for extended use.

While the results from Fairphone look promising there is a factor that is easily overlooked. Fairphone has only sold 94,985 mobile phones across 2020[16], and while Covid-19 might have impacted sales they still only represent 0.007% of 2020 cellphone sales. Research has shown that simply designing smartphones to last longer might not be enough to increase the functional lifespan of smartphones due to consumer habits[15].

5. MODEL DESIGN

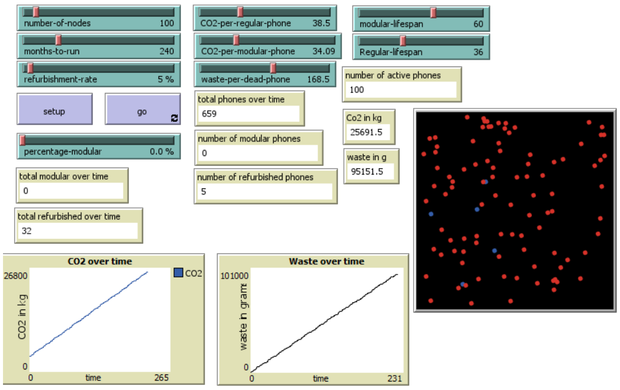

number-of-nodes 100
months-to-run 240
refurbishment-rate 5 %
percentage-modular 0.0 %
CO2-per-regular-phone 38.5
CO2-per-modular-phone 34.09
waste-per-dead-phone 168.5
modular-lifespan 60
Regular-lifespan 36
number of active phones 100
total phones over time 659
number of modular phones 0
number of refurbished phones 5
total modular over time 0
total refurbished over time 32
Co2 in kg 25691.5
waste in g 95151.5

Figure 1: Interface of climate impact model.

This section provides a detailed explanation of how the model was constructed. For an explanation of the different parameters of the model see paragraph 6. A guide on how this model can be installed is provided in Appendix 1. A brief explanation of the model code is provided in Appendix 2.

This ecological impact model provides a user-friendly interface to calculate the effectiveness of a given smartphone business strategy. The model uses some chance to represent the real-life variation of smartphone lifecycles. This model is agent-based meaning that each smartphone in use is modeled as an entity. These agents can be in three different states:

A non-refurbished regular smartphone.

A refurbished regular smartphone

A modular smartphone.

Table 4: chosen values emissions and e-waste for simulation

Model	CO2 emissions in kg	e-waste in grams	Lifespan in years
Regular	38.5	138	3
Modular	34.09	168.5	5

The values in Table 4 were determined by examining the LCAs of various smartphone models. The amount of waste and CO2 emissions of regular smartphones in Table 4 is based on the average amount of emissions and e-waste determined across multiple LCAs[12]. Because Fairphone 2 and 3 are the only current cases of modular smartphone design the estimations of their ecological impact were used for the CO2 emissions and e-waste of modular smartphones.

Regular phones represent current day industry-standard smartphones. The lifespan of regular smartphones lifespan is based on the average lifespan of a Lithium-Ion battery[13]. Modular phones are designed for parts to be easily replaceable resulting in a longer potential lifespan for the device. Every three years these agents need to have their battery replaced. The impact of this battery are 1.5 kg of CO2 and 65 grams of waste[22]. The average assumed lifespan of a modular smartphone is 5 years, based on estimations made by Fairphone[22].

The starting value of the lifespan of agents is randomized during the setup to simulate an age range for models. After the setup, the model no longer uses randomization in the lifespan. This decision was made because the average lifespan is already used to determine the time of death.

As old regular smartphones are replaced they have a percentage chance of being refurbished. To be refurbished in this simulation means to receive a full second life as a regular phone after which there is no chance for an extension. Modular smartphones cannot be refurbished seeing as after 5 years of intense use the hardware is outdated and worn out, unsuitable for reuse.

To simulate the repairs and cleaning required should a smartphone be deemed suitable for refurbishment, the additional cost of 3.5 kg CO2 and 83 grams of e-waste are added to the total amount. These emissions and waste are based on the replacement of the screen and battery, these are the parts that will most likely need replacing before resale. The emissions and weight of these components were taken from the Fairphone 3 LCA[22] because it was the only available source for this information.

It should be noted that Fairphone's models are developed with environment-friendliness in mind. This leads to Fairphone producing a more emissions-friendly model than its competitors. To create a fair field of comparison between the effectiveness of modular and regular business strategies, additional calculations were done assuming modular phones produce the same amount of emissions and e-waste as regular smartphones. The results of these simulations can be found in Section 6 as Modular reg.

Sadly, this model does not completely model the real world. The most glaring of differences is that the population has a set amount of agents whereas the real world of course has an expanding smartphone market. Also, regular smartphones are never repaired or broken prematurely.

The design decision to maintain a static population was made because it would otherwise result in an unfair advantage for the regular and refurbishment strategies. At first, this model used a simulation that created more new devices each turn, subtracting one from the total that had to be created if a smartphone was refurbished. This led to the modular strategy having more devices active than the other two strategies and thus having higher emissions and e-waste.

6. SIMULATION RESULTS

For design choices and settings of the model see section 5. Section 6.1 covers the results retrieved by assuming full deployment of each strategy. Section 6.2 covers the results retrieved assuming a more realistic adoption of 5% of both the modular and refurbished strategies. Averages per phone are calculated by dividing the total by 758.2, the average amount of regular phones in a simulation without business strategies applied.

This model offers a wide range of values that can be used to examine each of the three strategies well. Below each option and its effect on the simulation will be briefly explained.

The number of agents in the system can be changed at any time during simulation through the *number-of-nodes* slider. This has been set at 100 for both datasets.

The model runs for a set amount of cycles, each cycle has been set to simulate a month. The *months-to-run* slider is used to change the number of months to simulate. This has been set at 240 for both datasets.

The *refurbishment-rate* slider is used to change the percentage chance that an old regular phone gets refurbished. Set at 100 and 5 respectively.

The *percentage-modular* slider is used to change the percentage chance that a new phone will be modular. Set at 100 and 5 respectively.

The *CO2-per-modular/regular-phone* sliders are used to change the amount of CO2 emissions produced during the creation of the modular and regular phones respectively. The modular CO2 was set at 34.09 for the Modular mod data and 38.5 for the Modular reg data. Regular CO2 was set at 38.5 for all datasets.

The *waste-per-dead-phone* slider is used to determine how much waste a phone produces when it is retired. Set at 138 for the regular phones and 168.5 for the modular phones.

The *modular/regular-lifespan* sliders are used to set how many months a modular- or regular phone lasts respectively. Modular lifespan was set at 60 and regular lifespan was set at 36.

A simulation can be started by first pressing the *setup* button, which returns the system to its default state, followed by pressing the *go* button.

6.1 100% deployment of business strategies

Table 5: estimation of actual effectiveness for CO2 emissions 100% deployment

Strategy	**CO2 total**	**CO2 per phone**	**Difference**	**Difference %**
Regular	29,190.7	38.5	-	-
Modular reg	22,620	29.83	-8.67	23
Modular mod	20,389.42	26.89	-11.61	30.1
Refurbished	18,770.55	24.76	-13.74	36

Table 6: estimation of actual effectiveness for waste 100% deployment

Strategy	**waste total**	**waste per phone**	**Difference**	**Difference %**
Regular	104,631.6	138	-	-
Modular reg	82,576	108.91	-29.09	21
Modular	97,383.4	129.36	-8.64	6.3

mod				
Refurbished	76,873.8	101.39	-36.61	26.5

Table 7: estimation of total e-waste reduction per strategy 100% deployment

Strategy	Total waste	Waste difference from regular
Regular	104,631.6	-
Modular mod	97,383.4	-7,248.2
Refurbished	76,873.8	-27,757.8

Table 7 shows that even though modular smartphones produce more e-waste per device the overall strategy is still able to reduce the amount of e-waste the smartphone industry produces.

6.2 5% deployment of business strategies

Table 8: estimation of actual effectiveness for CO2 emissions 5% deployment

Strategy	CO2 total	CO2 per phone	Difference	Difference %
Regular	29190.7	38.5	-	-
Modular reg	28327.75	37.36	-1.14	3.0
Modular mod	28063.2	37.01	-1.49	3.9
Refurbished	27824.8	36.70	-1.8	4.7

Table 9: estimation of actual effectiveness for waste 5% deployment

Strategy	waste total	waste per phone	Difference	Difference %
Regular	104631.6	138	-	-
Modular reg	101639	134.05	-3.94697	2.86
Modular mod	102452.2	135.13	-2.87	2.08
Refurbished	99557.4	131.31	-6.692	4.8

Table 10: estimation of total e-waste reduction per strategy 5% deployment

Strategy	Total waste	Waste difference from regular
Regular	104631.6	-
Modular	102452.2	-2,179.4
Refurbished	99557.4	-5,074.2

7. CONCLUSION

Combining the information retrieved during the literature review and the insights gleaned from the simulation model the following conclusions can be made.

Examination of LCA data shows that the smartphone companies that have released LCA data seem to focus on production process streamlining. The best example of this was Apple being able to halve their emissions across generations. Apple's LCAs also show that even though emissions were reduced multiple times emissions keep increasing by a speed of 3 kg CO2 per generation. When Apple's products are compared to the Huawei models and others[12] Apple seems to be better than some competitors at reducing their emissions.

Fairphone seems to be able to deliver modular devices with lower emissions than regular market competitors. It is unknown if this is due to their modular design or if it is achieved through other environmental efforts. Fairphone's design is slightly bulkier than regular phones and is also slightly heavier. While Fairphone has been successful it is only one company so equating Fairphone's success to modular technology might be wrong, it does, however, show the potential of modular smartphone technology.

The final strategy, focusing on refurbishment, is also the least well-described strategy. Very little information exists about the refurbishment market. This might be attributed to the refurbishment market being a recycling market and largely consisting of smaller companies. At the time of writing Apple is the only smartphone company that does in-house refurbishing. While refurbished devices from other smartphone brands do exist these are always offered by smaller third-party companies. This makes it very difficult to determine the market size or the standards of the refurbishment industry. It should be noted that there is a cap to the number of phones that could be refurbished because not every phone is suitable for refurbishment and new phones will still have to be purchased for there to be devices to refurbish.

The model results show that both refurbishing and modular smartphone strategies can reduce emissions and generated e-waste. Modular technology is slightly less efficient than refurbishment. Full deployment of both strategies shows that refurbishment would be 5.9% more efficient at reducing CO2 emissions than modular technology. Refurbishment is much more efficient at reducing e-waste than modular technology with a 26.5% reduction compared to 6.3% for modular strategies. Full deployment of either strategy is unfeasible but at 5% deployment refurbishment is still the more efficient strategy with 36.7 kg of CO2 emissions and 131.31 grams of e-waste per phone.

Table 10 shows that at a 5% employment of business strategies both modular as well as refurbishing strategies can reduce the total amount of e-waste produced by the smartphone industry. Comparison with Table 7 shows that the modular strategy scales worse than the refurbishing strategy in its ability to reduce the amount of e-waste, this is due to the heavier design of modular smartphones.

8. DISCUSSION

As has already been discussed multiple times in this paper there currently is very little information available about the climate impact of smartphones. For refurbishment and modular technology, this can be attributed to both strategies being relatively new concepts. The development of these strategies would also require extra funds most smartphone companies don't seem to want to expend. Refurbishing has the added disadvantage of being a side business[19].

At the time of writing few prominent phone companies are releasing LCA reports on their smartphone products. This might be due to companies not wanting their emissions known or simply not wanting to invest in climate change technology. This unavailability of data led to certain assumptions about the ecological impact of smartphones, therefore not all results retrieved are reliable.

Another hurdle for the execution of this research was the constraint in time. While results and conclusions can luckily be drawn from this research a time constraint of fewer than 10 weeks is very short. For example, Dr. Balde suggested that an owner of a refurbishment business could be interviewed to ascertain the number of phones that get refurbished each year. While this was a very good idea it came when there were only three official weeks left to complete the first draft.

For this research, we also reached out to Fairphone for a possible interview however after initial enthusiasm, contact petered out. It is unknown how much this interview would have contributed to the overall research but it would certainly have provided a better overview of the ecological impacts of modular smartphones.

While the LCA assessments of Apple, Huawei, and Fairphone all seem to conform to market standards[12], it should be noted that these reports are released for promotional and commercial purposes.

Emissions are a somewhat vague concept of ecological impact. For example, the source of electricity largely impacts the amount of emissions. Most smartphone components are produced in Asia which have electricity mixes with high CO2 emissions[12].

Should research into possible alternative strategies like Rizos et al.[23] be conducted in the future they might now use this research and model to substantiate their claims. Hopefully, this research can be repeated similarly to Belkir et al.[11] to provide a more thorough example that these alternative strategies are indeed more effective at reducing emissions.

9. FUTURE WORK

While interviews with for example the refurbishment company and Fairphone fell through it would benefit the field of smartphone ecology if they were conducted.

If more data on the ecological impact of smartphones ever become available this research should be repeated. This will then hopefully lead to a more solid case for any of the three business strategies.

The current model for determining the emissions and waste is a relatively simplistic model lacking some of the variables that are present in daily life such as dropping your phone or a growing mobile phone market. For future research, it might therefore be interesting to update and upgrade this basic model so that the results it produces can lead to better decision making.

REFERENCES

[1] Apple Inc, iPhone 4 Life Cycle Assessment, (2010) https://www.apple.com/environment/pdf/products/archive/2010/iPhone_4_Product_Environmental_Report.pdf, accessed December 2021.

[2] Apple Inc, iPhone 5 Life Cycle Assessment, (2012), https://www.apple.com/environment/pdf/products/archive/2012/iPhone5_PER_sept2012.pdf, accessed December 2021.

[3] Apple Inc, iPhone 6 Life Cycle Assessment, (2014), https://www.apple.com/environment/pdf/products/archive/2014/iPhone6_PER_sept2014.pdf, accessed December 2021.

[4] Apple Inc, iPhone 7 Life Cycle Assessment, (2017), https://www.apple.com/environment/pdf/products/iphone/iPhone_7_PER_sept2017.pdf, accessed December 2021.

[5] Apple Inc, iPhone 8 Life Cycle Assessment, (2017), https://www.apple.com/environment/pdf/products/iphone/iPhone_8_PER_sept2017.pdf, accessed December 2021.

[6] Apple Inc, iPhone X Life Cycle Assessment, (2017), https://www.apple.com/environment/pdf/products/iphone/iPhone_X_PER_sept2017.pdf, accessed December 2021.

[7] Apple Inc, iPhone 11 Life Cycle Assessment, (2019), https://www.apple.com/environment/pdf/products/iphone/iPhone_11_PER_sept2019.pdf, accessed December 2021.

[8] Apple Inc, iPhone 12 Life Cycle Assessment, (2020), https://www.apple.com/environment/pdf/products/iphone/iPhone_12_PER_Oct2020.pdf, accessed December 2021.

[9] Apple Inc, iPhone 13 Life Cycle Assessment, (2021), https://www.apple.com/environment/pdf/products/iphone/iPhone_13_PER_Sept2021.pdf, accessed December 2021.

[10] Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann, P.: The Global E-waste Monitor – 2017, United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna. (2017), https://ewastemonitor.info/wp-content/uploads/2020/11/Global-E-waste-Monitor-2017-electronic-spreads.pdf, accessed November 2021.

[11] Bridgens, B., Hobson, K., Lilley, D., Lee, J., Scott, J.L. and Wilson, G.T.: Closing the Loop on E-waste: A Multidisciplinary Perspective. Journal of Industrial Ecology, 23: 169-181., (2019), https://doi.org/10.1111/jiec.12645

[12] Clément, L., Jacquemotte, Q., Hilty, L., Sources of variation in life cycle assessments of smartphones and tablet computers, Environmental Impact Assessment Review, Volume 84, (2020), ISSN 0195-9255, https://doi.org/10.1016/j.eiar.2020.106416

[13] Clemm, C., Mählitz, P., Schlösser, A., Rotter, V., Lang, K.: Umweltwirkungen von wiederaufladbaren Lithium-Batterien für den Einsatz in mobilen Endgeräten der Informations- und Kommunikationstechnik (IKT), TU Berlin, Herausgeber: Umweltbundesamt, Dessau-Roßlau, (2016), https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_52_2016_umweltwirkungen_von_wiederaufladbaren_lithium-batterien_0.pdf

[14] Cordella, M., Alfieri, F., Clemm, C., Berwald, A., Durability of smartphones: A technical analysis of reliability and repairability aspects, Journal of Cleaner Production, Volume 286, (2021), ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.125388

[15] Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E., Nilsson, E., Life Cycle Assessment of a Smartphone. pp. 124–133, (2016), https://doi.org/10.2991/ict4s-16.2016.15.

[16] Fairphone Inc, Environmental Impact Report 2020 Fairphone, (2020) https://www.fairphone.com/wp-content/uploads/2021/07/Impact-Report-2020-Fairphone.pdf, accessed December 2021.

[17] Forti V., Baldé C.P., Kuehr R., Bel G. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam. (2020) https://ewastemonitor.info/wp-

content/uploads/2020/11/GEM_2020_def_july1_low.pdf, accessed November 2021.

[18] Huawei: Life Cycle Assessment reports P9, P30, P50 plus. https://consumer.huawei.com/en/support/product-environmental-information/, accessed January 2022

[19] Ijomah, W.L., Bennett, J.P., Pearce, J.: Proceedings of the First International Symposium on Environmentally Conscious and Inverse Manufacturing, IEEE (1999, February), pp. 192-196, https://doi.org/10.1109/ECODIM.1999.747607

[20] Belkhir, L., Elmeligi, A.: Assessing ICT global emissions footprint: Trends to 2040 & recommendations, Journal of Cleaner Production, Volume 177, 2018, Pages 448-463, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2017.12.239

[21] Proske, M., Clemm, C., Richter, N.: Life Cycle Assessment of the Fairphone 2, (2016), https://www.fairphone.com/wp-content/uploads/2016/11/Fairphone_2_LCA_Final_20161122.pdf, accessed December 2021.

[22] Proske, M., Sánchez, D., Clemm, C., Baur, S.: Life Cycle Assessment of the Fairphone 3, (2019), https://www.fairphone.com/wp-content/uploads/2020/07/Fairphone_3_LCA.pdf, accessed December 2021.

[23] Rizos, V., Bryhn, J., Alessi, M., Campmas, A., Zarra, A. Identifying the impact of the circular economy on the fast-moving consumer goods industry. The European Economic and Social Committee (EESC), (2019). https://doi.org/10.2864/08334

[24] Sarath, P., Bonda, S., Mohanty, S., K. Nayak, S., Mobile phone waste management and recycling: Views and trends, Waste Management, Volume 46, (2015), Pages 536-545, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2015.09.013

[25] Statista, (O'Dea S.): Global revenue from smartphone sales from 2013 to 2020, (2021), https://www.statista.com/statistics/237505/global-revenue-from-smartphones-since-2008/, accessed January 2022.

[26] Statista, (O'Dea S.): Global market share held by leading smartphone vendors, (2021), https://www.statista.com/statistics/271496/global-market-share-held-by-smartphone-vendors-since-4th-quarter-2009/, accessed January 2022.

[27] Suckling, J., Lee, J. Redefining scope: the true environmental impact of smartphones?. *Int J Life Cycle Assess* **20,** 1181–1196 (2015). https://doi.org/10.1007/s11367-015-0909-4

[28] Tamar Makov, Colin Fitzpatrick, Is repairability enough? big data insights into smartphone obsolescence and consumer interest in repair, Journal of Cleaner Production, Volume 313, 2021, 127561, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.127561

[29] V. Weelden, E., Mugge, R., Bakker, C.: Paving the way towards circular consumption: exploring consumer acceptance of refurbished mobile phones in the Dutch market, Journal of Cleaner Production, Volume 113, (2016), Pages 743-754, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2015.11.065

[30] Zufall, J., Norris, S., Schaltegger, S., Revellio, F., G. Hansen, E., Business model patterns of sustainability pioneers - Analyzing cases across the smartphone life cycle, Journal of Cleaner Production, Volume 244, (2020), ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.118651

Appendix 1: Netlogo Model installation instructions

1. Go to the Netlogo website at https://ccl.northwestern.edu/netlogo/
2. Download the newest version suitable for your device
3. Install Netlogo on your PC
4. Download the model from this google drive: https://drive.google.com/file/d/1mz3kjcFgOcrG1jbDAm8hJvgVWTaKssYk/view?usp=sharing
5. You can then open the .nlogo file using the Netlogo application.
6. For an explanation on how to run the model see the Method of Research section

APPENDIX 2: CODE SUMMARY

The following appendix contains a brief overview of the Netlogo code. The code will be explained in the order that it appears.

Globals

These values are used to track all the total values of the system. For the usage of each value please see the comments in the image below.

Turtles Own

This section describes the variables that each agent has. The agent keeps track of if they are modular or refurbished. Agents also track their lifespan and if they are close to being repaired.

Setup

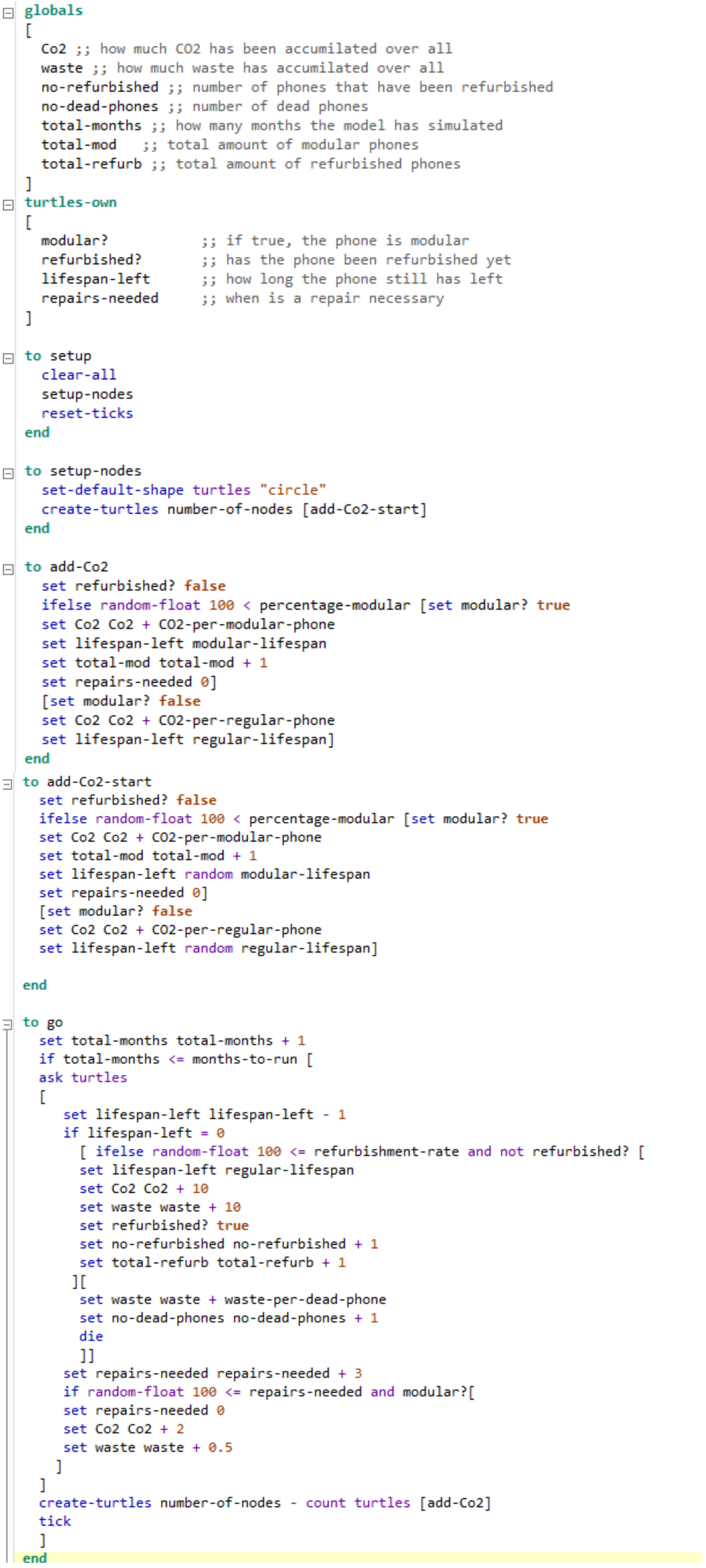
Setup clears the board and then sets it back up. For each of the agents, it runs a special version of the add-Co2 which randomizes the amount of lifecycle left.

Add-Co2

Add-Co2 is a function used during the initialization of new agents. It first determines if the new agent is modular or not using a random chance generator after which it then sets the values to their respective places. Add-Co2-start is identical to this function with the exception that the initial lifespans are randomized.

Go

This is the core loop of the model. If a user clicks go this method will loop for the number of months set in the interface. The model first ages the agents and then checks if the lifespan is zero. If it is zero then regular phone agents have the chance to get refurbished. Modular phones that reach zero and regular phones that do not get refurbished get added as waste. Phones that get refurbished incur a bit more cost in waste and repair because the phones will need to have some parts replaced and need to be thoroughly cleaned. After the broken phones have been handled all remaining modular phones are checked if they need repairs. If repairs are needed a small cost of CO2 and waste is added to simulate the purchase and fabrication of a new module. It then creates a number of new agents equal to the number that died during the cycle.



```
globals
[
  Co2 ;; how much CO2 has been accumilated over all
  waste ;; how much waste has accumilated over all
  no-refurbished ;; number of phones that have been refurbished
  no-dead-phones ;; number of dead phones
  total-months ;; how many months the model has simulated
  total-mod   ;; total amount of modular phones
  total-refurb ;; total amount of refurbished phones
]
turtles-own
[
  modular?           ;; if true, the phone is modular
  refurbished?       ;; has the phone been refurbished yet
  lifespan-left      ;; how long the phone still has left
  repairs-needed     ;; when is a repair necessary
]

to setup
  clear-all
  setup-nodes
  reset-ticks
end

to setup-nodes
  set-default-shape turtles "circle"
  create-turtles number-of-nodes [add-Co2-start]
end

to add-Co2
  set refurbished? false
  ifelse random-float 100 < percentage-modular [set modular? true
  set Co2 Co2 + CO2-per-modular-phone
  set lifespan-left modular-lifespan
  set total-mod total-mod + 1
  set repairs-needed 0]
  [set modular? false
  set Co2 Co2 + CO2-per-regular-phone
  set lifespan-left regular-lifespan]
end
to add-Co2-start
  set refurbished? false
  ifelse random-float 100 < percentage-modular [set modular? true
  set Co2 Co2 + CO2-per-modular-phone
  set total-mod total-mod + 1
  set lifespan-left random modular-lifespan
  set repairs-needed 0]
  [set modular? false
  set Co2 Co2 + CO2-per-regular-phone
  set lifespan-left random regular-lifespan]

end

to go
  set total-months total-months + 1
  if total-months <= months-to-run [
  ask turtles
  [
     set lifespan-left lifespan-left - 1
     if lifespan-left = 0
       [ ifelse random-float 100 <= refurbishment-rate and not refurbished? [
       set lifespan-left regular-lifespan
       set Co2 Co2 + 10
       set waste waste + 10
       set refurbished? true
       set no-refurbished no-refurbished + 1
       set total-refurb total-refurb + 1
      ][
       set waste waste + waste-per-dead-phone
       set no-dead-phones no-dead-phones + 1
       die
       ]]
     set repairs-needed repairs-needed + 3
     if random-float 100 <= repairs-needed and modular?[
     set repairs-needed 0
     set Co2 Co2 + 2
     set waste waste + 0.5
    ]
  ]
  create-turtles number-of-nodes - count turtles [add-Co2]
  tick
  ]
end
```