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Life Cycle Sustainability Assessment:
One-time Disposed vs. Reprocessed Masks

1. Executive Summary

This Life Cycle Sustainability Assessment (LCSA) evaluates the sustainability of one-time disposed vs. reprocessed masks. To control the spread of the virus, the use of face masks has become the norm. Studies have shown that 3.4 billion face masks are discarded every day, which in turn generates a large amount of waste that we yet to find a sustainable way to recycle [9]. On the other hand, a process for steam sterilization of face masks has undergone a series of developments and has received more attention. Used face masks that are being sterilized and reproduced are being referred to as “reprocessed face masks.” Several measures have been put in place to ensure the quality of such masks and their effectiveness to prevent viruses [12]. However, questions arise about this new product compared to the traditional one, which urges the need of a holistic approach for examination regarding the three pillars of sustainable development: environmental, economic, and social.

This study mainly addresses the healthcare system in the U.S. where we see an ongoing need for face masks before and during the pandemic. Hospitals are an ideal starting point to experiment the implementation of reprocessed masks. By going through the life cycle stages including production, use, and end-of-life, we found that the reprocessed masks are indeed a better option across all pillars, likely due to its greater success in protecting the same group of healthcare workers using less overall materials. Despite the apparent outcome, this study should be used as a jumping off point for future more rigorous research since there are several limitations including data quality and lack of peer review process.

2. Goals and Scope

During the pandemic of the past two years, wearing a mask has become a social norm across the globe. How to produce, use, and dispose of masks has become a topic of concern in many contexts, especially that of a healthcare system. The primary goal of this study is to compare the environmental, economic, and social impact of one-time disposed vs. reprocessed face masks. The study is intended to be used primarily by hospitals where an ongoing use of face masks is needed and recycling of used face masks is most likely. The intended application of this study is to assist in the decision making process of hospitals and healthcare workers when choosing which kind of masks to wear. The intended audience is the management teams for hospitals as well as decision makers of the healthcare system in the United States. There are several limitations of this study. One limitation is that this study does not intend to consider the cost of transportation, holding, and distribution of masks. Instead, it is focused on the phases of production, use, and disposal. Moreover, the study does not use any formal methods of S-LCA analysis and will not submit for peer review. In this case, the study serves as a jumping off point for future research.

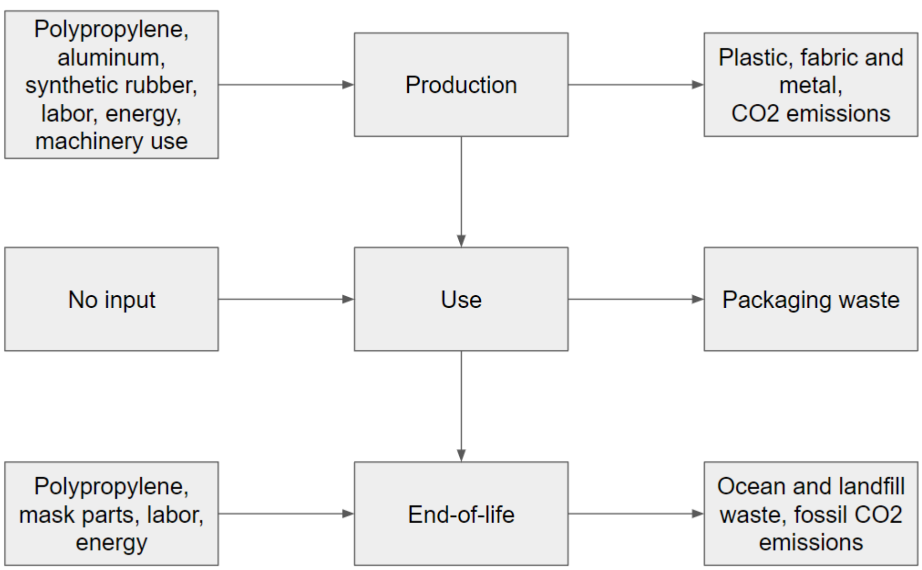
The scope of this project focuses on comparing disposable face masks that are used only once with those that were sterilized and reused up to three times. The system function is to produce, use, and reuse disposable face masks for healthcare workers while improving the health and well-being of people in the healthcare system. The system boundaries are the disposable medical masks being produced and used within the U.S. healthcare system. The functional unit is the protection of 100 healthcare workers against air transmitted viruses, using one medical mask during one work shift.

3. Environmental LCA

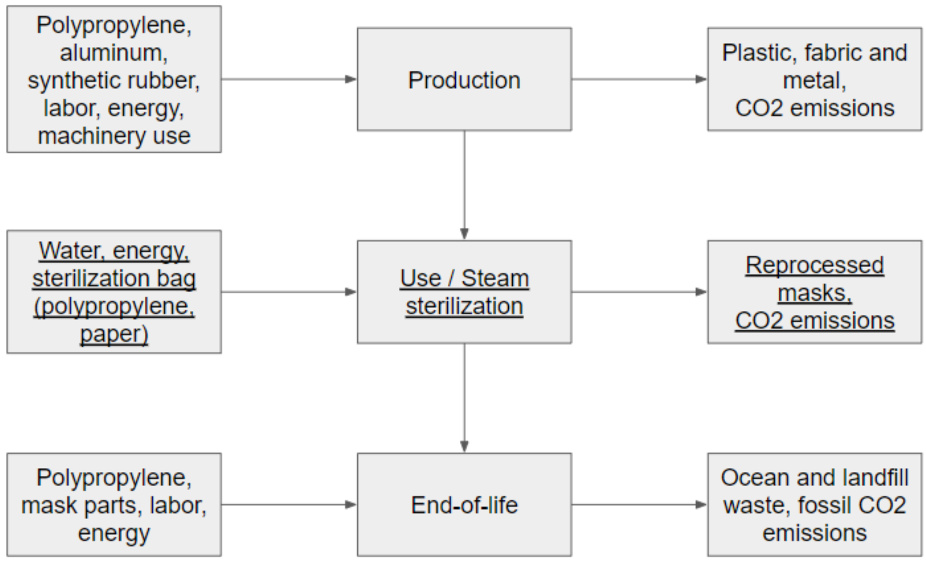
The Environmental LCA intends to cover stages of the life cycle including production, use, and end-of-life, in order to best compare the environmental impact between one-time disposed vs. reprocessed masks. Though the inputs and outputs for the two would be similar during the production stage, they are quite different during the use stage, because of the extra steam sterilization and quality control in need for the reprocessed masks. The end-of-life stage would also be included in order to account for the effect of the amount of waste produced by the two products.

3.1 Life Cycle Inventory

Disposed mask life cycle inventory:



Reprocessed mask life cycle inventory (difference underlined):



Production

Textile, non-woven polypropylene is the main material for the production of disposable masks. In addition, the nose clips of some masks are made from aluminum. The elastic straps are made of fiber or synthetic rubber, depending on the specific type of the masks [12] . Moreover, there is human labor, heat and electric energy, as well as machinery use going as input into the production stage. The output of this stage includes plastic, fabric and metal, as well as CO_2 emissions [5] .

Use

For disposed masks, there is no input into the use stage. The only output coming out of this stage is packaging waste. However, for reprocessed masks, this stage consists of steam sterilization that is required to reuse masks. During this process, sterilization bags, tap water, electricity, as well as time and labor are necessary inputs. Outputs include reprocessed masks, quality control / rejection rate, as well as wastewater and CO_2 emissions [12] .

End-of-life

Finally, during the end-of-life stage, the inputs include polypropylene, mask parts, labor and energy. The output includes ocean and landfill waste, fossil CO2 emissions [9]. Note that currently many researches have been conducted to study various methods to reduce waste during this stage. They are out of scope of this project and will not be discussed in detail.

3.2 Life Cycle Impact Assessment

Climate change is the major midpoint impact category that will be impacted by the inputs and outputs of the life cycle inventory. The carbon footprint (kg CO2 eq) is the primary unit of measurement of such impact. During manufacturing, raw materials have to be sourced, melted and assembled with labor and machinery, leading to a total of 1850 kg CO2 eq emission in this process. Moreover, during the incineration process of the end-of-life stage, an estimate of 1487.37 kg CO2 eq emission occurred [5]. All these emissions contribute to the accumulation of greenhouse gases, which lead to global warming, mass extinction, as well as smog and air pollution.

The other three major categories that would be impacted are land use, water use, and human toxic effects from the end-of-life stage of the masks. When the non-reusable plastic becomes waste and goes into land and water, they can fragment into small particles of microplastics. It takes approximately 450 years for them to biodegrade, and in turn poses a serious threat to the land and water environments [11]. Those plastics not only impact terrestrial and aquatic habitats, they can potentially cycle back into the food and water of human consumption and pose human toxic effects [11]. Study shows that during the recent COVID-19 pandemic, more than eight million tons of plastic from medical waste have been generated globally, with more than 25,000 tons entering the global ocean [8]. This poses a long-lasting problem for the ocean environment and would be accumulated on beaches and coastal sediments.

3.3 Interpretation

This analysis shows the processes within the life cycle of both disposed and reprocessed masks lead to significant environmental impact, including climate change, water and air pollution, and human toxic risks. Since the reprocessed masks can be reused up to three times, they constitute essentially only a third of the end-of-life waste of one-time disposed masks. Compared to the tremendous contribution to CO2 emission during the end-of-life stage, the use of water, energy, and material during the sterilization phase of reprocessed masks are very small. Therefore, reprocessed masks are a lot more eco-friendly and should be considered as a more sustainable option. However, there are limitations to the study. The data of exactly how much carbon footprint would be needed during the steam sterilization process of reprocessed masks is missing, making it difficult to calculate the exact number of emission reductions compared to disposed masks. Moreover, the rejection rate of the reprocessed masks is also vague depending on situations (deformities, lipstick, broken elastic bands, etc.). If the reprocessed masks are made known to the public, especially the healthcare workers in the scope of the system, they may take better care of the masks and in turn foster higher reprocessing rates. Similarly, user habits of masks can be studied in further detail to account for more accurate interpretations.

3.4 Response to Review

Comments	Responses
Peer comment: "I think you should provide some more information about the impacts on the land and ocean. I am sure there are many statistics about the amount of waste from the mask mandate and its implications on the environment.	I agree. With more information the audience can better understand the comparison between these two products. In response, I have researched more into the impact of waste on land and ocean, and provided specific data on the subject.
TA comment: "Well done describing each stage but points were taken off because you did not talk about how and why this will affect your analysis. Try to include a short paragraph explaining overall how this analysis affects	I did have some explanations, but they might not have been enough. In response, I have added more to the interpretation section to reflect how the inputs and outputs at each stage affect my analysis.

your paper."	
Self comment: The two diagrams I had before for life cycle inventory were hard to discern. It takes some time for the readers to find out the difference between the two.	To highlight the difference between the two products, I underlined the change for reprocessed masks in the bottom diagram. This will help the audience to see what changed at what stage more clearly.

4. Life Cycle Costing (LCC)

This LCC aims to compare the aggregation of all costs that are associated over the life cycle of one-time disposed vs. reprocessed face masks. The study is intended to take the perspective of hospitals as well as stakeholders in the healthcare system in the United States, where cost is a big factor when they make a decision.

4.1 Inventory and aggregate costs by cost categories

Life cycle stages	Disposed($)	Reprocessed($)
Production	75	25
Use	5	5
Reprocess	0	18
End-of-life	45	15
Total	**125**	**63**

Table 1. Costs accounting for disposed and reprocessed masks during different life cycle stages

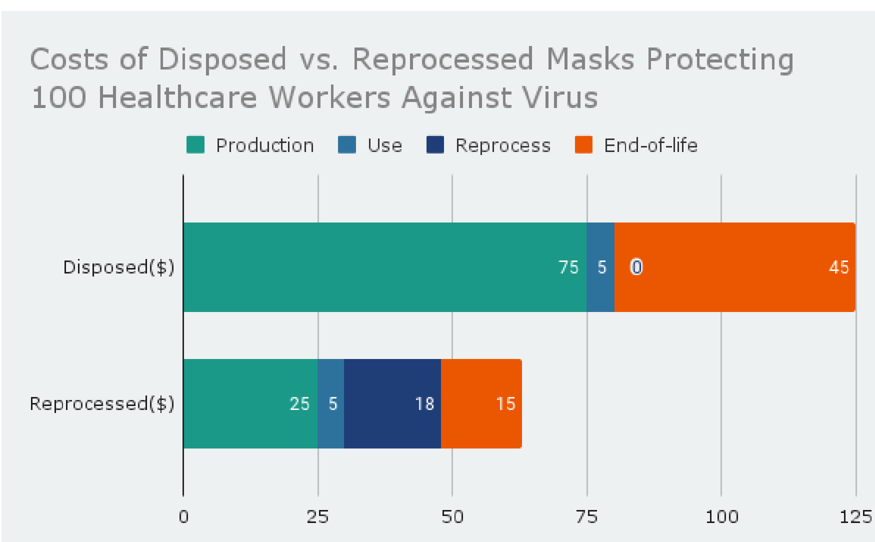


Figure 1. Costs of disposed vs. reprocessed masks protecting 100 healthcare workers

Table 1 and Figure 1 show the costs associated with disposed and reprocessed masks protecting 100 healthcare workers against air transmitted viruses, using one medical mask during one work shift. We also make the assumption that each mask can be used and repossessed up to three times [12]. During the production phase, the system cost of the labor and manufacturing as well as water and electricity are calculated and then adjusted proportionally to represent the functional unit. Since all masks coming out of production are “new” disposable masks, the total cost in this stage is $75 for disposed and $25 for reprocessed [6]. During the use phase, an estimate of $5 dollars is accounted for both types of masks considering distribution costs and possible damage during transportation. During the reprocess phase, only the reprocessed masks are in need of reprocessing, and the estimated cost associated with this type of mask is $18 [13]. Finally, there are costs during the end-of-life recycle phase for both types of masks. These costs are most variable due to the different actions that could be taken during the recycling process. If the used masks directly go into landfill, this cost can be as large as $280, but if we use mechanical or chemical methods to recycle the different components of masks, this cost can get down to $30 [12]. Considering the actions taken as shown in Hu’s report [3], we reason this cost to be $45 and $15 respectively in our case for healthcare workers given their collected efforts for waste management.

4.2 Interpretation

The above analysis of the aggregated costs shows that the costs of reprocessed masks are reduced by 50% from the ones that are directly disposed from one time usage. Therefore, while reprocessed masks require the additional sterilization process, its savings in the end-of-life stage offset its cost, making it more economically beneficial than the one-time disposed masks. It is important to note that we made assumptions and estimations during the calculations. We assume that one worker would always use one mask during a shift. Starting a new shift, they will use a new mask, whether it is disposed or reprocessed. We also assume that each mask can reprocess up to three times. In addition, if more specific data is provided with a breakdown during the manufacturing period, as well as the costs during the specific healthcare hospital setting associated with the use of masks, we could make a more holistic cost analysis and arrive at a more accurate number. One thing we did not consider during this analysis is the cost associated with transportation and inventory holding. Limitations also include a lack of formal LCSA methods and a rigorous peer review process.

4.3 Response to Review

(Since there was no peer comment, I used one more TA comment to substitute)

Comments	Responses
TA comment: "Great job synthesizing your cost data into 2 figures—is there any way you could combine the figures to include the numerical costs on the bar graph? This may help with the readability of your figures."	This is a very good point. I have updated the figure to show the numerical costs on the bar graph. With this update, the figures are indeed more readable.
TA comment: "Good job highlighting the lower costs of reprocessed masks—can you draw any broader conclusions about the economic sustainability of both products?"	My previous conclusions were indeed a bit narrow when simply stating "the costs of reprocessed masks are reduced by 50%." Now I have added more extrapolation to the conclusion to comment on the economic sustainability of the products.
Self comment: Some costs were not accounted for, such as costs associated with transportation and inventory holding.	When I researched for more data, I found that the costs associated with transportation went up during COVID-19 because of the surge in demand and shortage in supply (OECD). However, it was hard to find a specific number to put on the table and graph. I then reasoned that since the transportation process would be mostly the same for both products, it is ok to leave this part out.

5. Social LCA

This S-LCA intends to compare the social impacts that are associated over the life cycle of disposed vs. reprocessed face masks.

5.1 Inventory

Relevant stakeholders within the two systems include the workers, local communities, consumers, as well as society at large. However, in this analysis, we only focus on two of these stakeholder categories and their two impact subcategories. Below are two impact subcategories and their associated stakeholder categories that will be considered in this study:

1. Worker: Safe and Healthy Living Condition
2. Local community: Health and Safety

5.2 Impact Assessment

Stakeholder Category	Impact Subcategory	Status	Human Rights	Working Conditions	Health and Safety	Cultural Heritage	Governance	Socio-economic Repercussions	Assessment
Local Community	Safe and Healthy Living Conditions	Is at risk. The disposed face masks can release pollutants including lead, antimony, and copper to land and water, in turn harms the living conditions of the local community.	✓	✓	✓	✓	✓	✓	At risk
Worker	Health and Safety	Is at risk. The workers are in toxic environments and are exposed to flammable and corrosive chemicals. They also perform repeated tasks that may lead to blisters, muscle injuries and mental disorders.	✓	✓	✓	-	✓	✓	At risk

The table above displays the social impacts of disposable face masks. Under the stakeholder category of the local community, safe and healthy living conditions of people in the community are at risk considering the production, use, and disposal of masks. Especially during the end-of-life disposal phase, the masks can release pollutants including lead, antimony, and copper. The waste that has bio-accumulative properties can have a substantial environmental impact by simply exposing the material to water, which in turn can be consumed by humans [10]. All six main impact categories are at risk. Everyone has the right to live and to be safe, but the improper recycling of masks puts this human right at risk. The toxic environment can also pose danger to the working environment, as well as the health and safety of individuals. Cultural heritage of a safe living environment for future generations is also endangered by such pollution. Governance of the system must be put into place to hold people accountable and foster a better mechanism to resolve the problem. Finally, socio-economic repercussions are significant if the problem remains unsolved, and that people living especially nearby landfill or water are greatly affected by the pollutants, their living conditions also continue to deteriorate [10]. Eventually, either more dollars must be spent for the remediation, or more lands become contaminated and inhabitable.

Under the stakeholder category of the workers, their health and safety should also be taken into account when assessing the impact of masks. Factory workers in the U.S. had an injury and illness rate of 6.6 per 100 compared to 2.8 per 100 for workers overall [2]. Factory workers work in toxic environments and are exposed to chemicals that are flammable and corrosive. They also perform repeated tasks that may lead to blisters and muscle injuries and mental disorders [2]. Even though there are policies present for workers and worker unions to protect their human rights, the working conditions are still severe for the factory workers. During the pandemic when the consumption of face masks increased dramatically, the workload of the workers also increased far beyond the standard. Not only were their physical health under torment, their mental health was being oblivious to their managers. 33.5% of the workers had poor mental health, especially anxiety and insomnia [7]. On one hand, they had to keep working to meet the high demand of masks; on the other hand, the virus was also circulating among the workers and put their own health at risk. Policies were not updated and put into place to respond to the evolving situation, and the socio-economic repercussions were severe.

5.3 Interpretation

The analysis shows that the local community and workers are very much impacted by the production, use, and end-of-life disposal of the face masks. Since we lack a formal method to recycle the masks, many toxic pollutants of the waste, plastic in large, go into the environment and eventually would circle back and put human living conditions at risk. Therefore, it is imperative that we implement a workable mechanism to recycle the masks. Many studies have been done to explore different options of recycling, either mechanical or chemical [1]. Then the reprocessed materials can not only be used as new masks, but they can also be used as construction materials, furniture parts, or even supercapacitors [4]. However, in order for the technologies to actually be put into use, it is the role of the government and policy makers to work together with the local waste management. A starting point could be to ask people to recycle masks separately from other landfill waste. Moreover, the health and safety of the factory workers needs to be seen as part of the bigger picture. Measures are also needed to protect workers' working conditions and both physical and mental health. Their well-being is necessary for the society and economy at large.

Taking all into account, I can conclude that reprocessed masks serve the local community and workers better than one-time disposable masks with respect to their social impact. For reprocessed masks, we only dispose of them after they are reprocessed three times, compared to being disposed after one time use, which can ideally reduce the mask wastes and pollutants in the environment by two thirds, considering the same methodology of the end-of-life process. Moreover, when workers reprocess a used mask instead of making a new mask, they are exposed to significantly less harmful materials and could maintain a better health condition [7].

This S-LCA could benefit from having more data including the exact working hours and injuries of specifically mask factory workers instead of general factory workers. The exact measurement for the pollutants in the environment is also lacking. Some qualitative experience of the local communities nearby pollutant landfill and water or the factory workers could also provide a more humanistic view of the analysis. Another limitation is that there are only two stakeholder categories and two impact subcategories included in this study. If we take into account the perspectives of consumers and society, another problem arises, which is the public perception of wearing or buying repossessed masks. The current social norm in the healthcare workplace is that all equipment being disposed of after single use. After the validation of the same effectiveness of reprocessed masks, how to advertise the product and make it socially acceptable is imperative.

5.4 Response to Review

Comments	Responses
Peer comment: “One thing that I think you can improve is to address the public view of wearing or buying reprocessed masks. One big process that a lot of healthcare masks or even healthcare equipment in general are known for is that almost all equipment is disposed of after being used, be it masks or even some scalpels. Maybe you could include another subcategory about whether or not people will choose to wear a mask that has been reprocessed, even if it has been sterilized or recycled. ”	This is a very good point. I included a few sentences discussing this perspective in the interpretation. However, since we only pick two impact subcategories to analyze in this study, it is out of scope to go into detail and provide rigorous sources to support.
TA comment: “Good job discussing your findings! I would suggest taking out phrases such as ‘I think’ and ‘I see that,’ as your writing would be stronger without them!”	I took out these phrases in the final draft!
TA comment: “Good job with your narrative! One thing you might want to add: you say ‘Factory workers had an injury and illness rate of 6.6 per 100 in the U.S. ‘ and I think it would be interesting to compare that to the injury/illness rate of workers overall in the U.S. if you can find that data!”	I did find that workers overall have an injury/illness rate of 2.8 per 100, which is significantly lower! And I have included this finding in the final paper.
Self comment: When I organize the impact category titles in the tables as horizontal instead of vertical shown in the example, the texts appear to be small, broken, and hard to read.	I tried using the drawing tool under insert to make the texts vertical. However, the texts appear to be blurry when written from drawing. I chose to stick with the current table.

6. Conclusions

The previous analysis of LCA, LCC, and S-LCA has consistently shown that the reprocessed masks are more sustainable than the one-time disposed masks during their life cycles. The key life stage of masks is the end-of-life stage, which is where the most contribution to the environment and economy comes from. The key impact subcategory is safety and healthy living conditions of the local community. In LCA, we showed that although both products contribute to the environment, including climate change, water and air pollution, as well as human toxic risks, the output of reprocessed masks weighs smaller compared to disposed masks because of the smaller amount needed in the end-of-life stage considering a functional unit of 100 healthcare workers in one work shift. In LCC, we have also shown the costs of reprocessed masks are reduced by 50% compared to the one-time disposed masks regarding the same functional unit. The savings mostly come from the production stage as well as the end-of-life stage, when the same materials are reused up to three times by the health workers, which easily offset the cost of sterilization for reprocessed masks. Finally, in S-LCA, we showed that the stakeholders of local communities and workers are at risk because their health and safety are impacted. The toxic pollutants of the waste pose danger to the living environment of local residents. The factory workers also have a higher injury rate, especially during the pandemic when face masks had an upsurge in demand. In the end, reprocessed masks serve both the local community and workers better, as long as they provide the same protection against viruses and become more socially acceptable.

On the other hand, when we look at the bigger picture and take all three aspects into account, we would find that in reality it is still very hard to make the reprocessed masks win over the traditional one-time disposed masks. There are trade-offs. No doubt reprocessed masks are more environmentally friendly. The cost for one-time sterilization might be low, however, the setup of the whole reprocessing system can be of great cost. How to collect the waste, how to count the number of times a specific mask is reprocessed and if it still meets the accepting conditions, how to redistribute the reprocessed masks back to healthcare workers -- these are not easy problems and can carry immense economic and social burdens. Even when we have the technology, we still have a long way to go to make the system work. Looking in the long-term, I would suggest that reprocessed masks would save a lot in the future and it is worth the effort to introduce to the healthcare system.

This study is limited by data quality. All sources were found online. Though I used the CRAAP test for each of my sources to check for currency, relevance, accuracy, authority, and purpose, it may still lack certain information because some of which are not primary sources and we lack a formal method of peer review. I attempted to account for this by stating my assumptions and making limited conclusions.

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