TESTING AND DEVELOPING DIY MASKS

Final Report

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EXECUTIVE SUMMARY

The purpose of this design project is to develop a DIY mask to combat the shortage of N95 respirators and medical masks in low resource settings. In the preliminary stages of the project, meetings with stakeholders, mostly in the form of experts in the area of study, were conducted. Research was also done on literature in the area, which led to the development of engineering specifications. The mask should have a low cost of less than 2 cedis or 0.34 USD (Ama 2020). The mask should be made in less than 30 minutes with fewer than 12 steps of instructions (Centers for Disease Control and Prevention, 2020e; Bound Tree, 2020; Gierthmuehlen, 2020; Khong, 2020; Ama, 2020). The mask should filter over 50% of particles over 50 nm in size (Davies, 2013; Advances, 2006). The mask should fit well to the face and minimize air flow around the edge with a fit factor greater than or equal to 2 (Davies, 2013). The mask should also be comfortable to wear with average scores greater than 4 on a 6 point Likert scale (Purdy, 2019). Finally, the mask should sustain a long lifespan, supporting over 20 uses with a decontamination cycle in between each use (Oh, 2020; Centers for Disease Control and Prevention, 2020f).

Design heuristics were used for initial concept generation during a brainstorming session. This produced over 60 concepts which were then organized into a morphological matrix. From this point, 11 concept designs were made and evaluated using a decision matrix, producing a numerical ranking for the designs. The highest scoring design was a mask that had an additional nylon covering that could help in sealing the edges of the mask as well as improving filtration efficiency. This highest scoring design as well as the two subsequent designs were prototyped and tested.

Engineering analyses were developed to further evaluate the mask designs and answer some key design drivers. The first and simplest test was the Mask Fabrication Test, which simply recorded the time it took to create the masks. The test indicated that the three designs had a comparable fabrication time. The next substantial test that was conducted was the Mask Fit Test, which measured airflow around the masks. From this test, various factors of the best performing masks were determined. To help ensure the mask was comfortable, several steps were taken. First, a Comfort Priority Survey was conducted, which helped provide context for the results of the Mask Comfort Test. Then, prototypes of the three mask designs were tried on and rated for various aspects of comfort by people close to team members. From these tests, the nylon design was chosen as the final design, with a few modifications. The final design uses three layers of material -cotton, silk, and nylon- to filter out particles. The nylon layer also acts as the ear straps for comfortability. Wires are sewn inside the top and bottom of the mask to improve fit, and pleats are sewn on the side for flexibility. One final comfort test was conducted with the design, which verified the requirement. The low cost requirement was verified through calculations, and the “uses available materials requirement” was verified from research. The “is easy to create” requirement was verified with a use test. To verify the lifetime and filtration efficiency requirements, a Mask Filtration Efficiency Test was performed. However, due to a lack of testing time, no conclusive results were obtained from the test, and the lifetime and filtration efficiency requirements were left unverified. An inability to test also left the fit requirement unverified.

By the end of the project, a design and instructions on creating the design were created. This design has been verified to fulfill 4 out of 7 requirements. The filtration efficiency, lifetime, and fit requirements all require further testing for verification.

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PROBLEM DESCRIPTION AND BACKGROUND

Due to the COVID-19 pandemic, there is a shortage and a need for N95 respirators. Hospitals mostly use N95 respirators because of their high efficiency for filtering COVID-19 (Seladi-Schulman, 2020). In order to prevent the general public from using N95 respirators that are desperately needed in hospitals, the general public should focus on learning how to make their own in a way that enables them to stay safe during the pandemic. This need serves as the basis of this project and is why testing and developing DIY masks is so important.

The goal of the project is to create a DIY mask that effectively blocks the transmission of COVID-19 using materials common to low resource settings. The term "DIY" stands for "Do It Yourself", and typically defines a project that people can complete on their own with materials that are readily available. For the scope of this project, a DIY mask is a mask that the user can create and assemble on their own. The original target location for this project was Ghana, but it has since been expanded to include all low resource settings throughout the world.

Background

COVID-19 was first identified in Wuhan, China in December 2019 and has since then spread into a worldwide pandemic. The Coronavirus family primarily causes upper respiratory infections in humans. The symptoms that one may experience can range from common colds up to more serious illnesses or death, and the most common method of spread for COVID-19 is through droplet and airborne transmission (Liu, 2020). COVID-19 droplets can range in size from 50 nm to 200 nm in diameter (Bar-On, 2020). To prevent this transmission of particles, face coverings such as masks have been proven extremely helpful. Many different types of masks exist. Mask wearing practices vary from person to person, along with what someone looks for when wearing a mask. Some users want their mask to protect others from the transmission of viruses, some look for comfortable masks, and others want their mask to be breathable. Masks block the particle droplets that escape from the user's mouth, thus protecting others from the transmission of COVID-19 (World Health Organization, 2020). There are currently multiple tests that are practiced in order to determine a mask's filtration efficiency, fit to face, and comfortability (Konda, 2020; Davies, 2013; Purdy, 2019). These tests will be further explained in benchmarking. There are currently shortages of medical-grade masks such as the N95 respirator, causing an overall increase in the prices of masks. This brings into question cost-efficiency versus safety, especially in low resource settings. The general public is thus recommended to use DIY masks in order to slow the spread of COVID-19. These DIY masks can be washed and reused, and do not tax the supply of the medical masks that are needed by emergency workers (Liu, 2020; Centers for Disease Control and Prevention, 2020b). For low resource countries, complicated masks such as ones that are 3D printed or N95 respirators are not very common. DIY masks are much more readily available and when used correctly, can help slow the spread of the virus. A very serious issue with DIY masks is the fact that they do not block the transmission of COVID-19 as well as medical-grade masks such as a surgical mask or an N95 respirator (Centers for Disease Control and Prevention, 2020b). This is why it is so important to learn how to correctly create a mask that is both comfortable to wear and is effective in blocking the transmission of the virus.

Literature

Common literature sources that were used for this project were the University of Michigan Library, Google Scholar, and Science Direct. Some of the keywords that were commonly used when researching articles to use include: DIY masks, filtration efficiency, material comfort, decontamination, coronavirus, coronavirus transmission, mask fit, N95 respirators, and low resource settings.

Benchmarking

To pursue an end product that would meet or surpass current DIY mask solutions, various information sources were used to determine benchmarks. In some cases, these various information sources were synthesized to draw up assumptions on the average DIY mask performance.

A particularly important information source that was used was "How to Make Masks," a guide released by the CDC on creating DIY masks (Centers for Disease Control and Prevention, 2020e). The guide targets the general population and contains instructions for creating both a simple unsewn mask and for sewing a higher quality mask. The materials suggested in the guide, namely cotton and an elastic string or rubber band, were used as a reference for a cost benchmark. The list of steps to make the mask was also considered when deciding on creation time. However, this article does not do a good job of providing design alterations that would allow it to fit faces of different sizes. Three other DIY masks were benchmarked and are shown in Figure 1 (page 6) below along with the CDC Non-sen Mask. The Vanderbilt Sewn Mask is similar to the sewn mask proposed by the CDC but has a folded exterior that allows for expansion and contraction when speaking so as to prevent the mask from sliding off of one's face (How, 2020). However, a lack of wiring or support over the nose makes it easier for gaps to form between the mask and one's face. The CNN Sewn Mask is also similar to the sewn mask from the CDC but is more symmetrical and uses a coffee filter for added filtration (Andrew, 2020). Although the coffee filter provides added filtration, the lack of wire over the nose allows for gaps to form leading to poorer fit. The T-shirt Mask is made from a t-shirt and does not require any sewing (Skillset Staff, 2020). However, cotton t-shirts are typically loosely woven and therefore are worse at filtering out coronavirus particles.

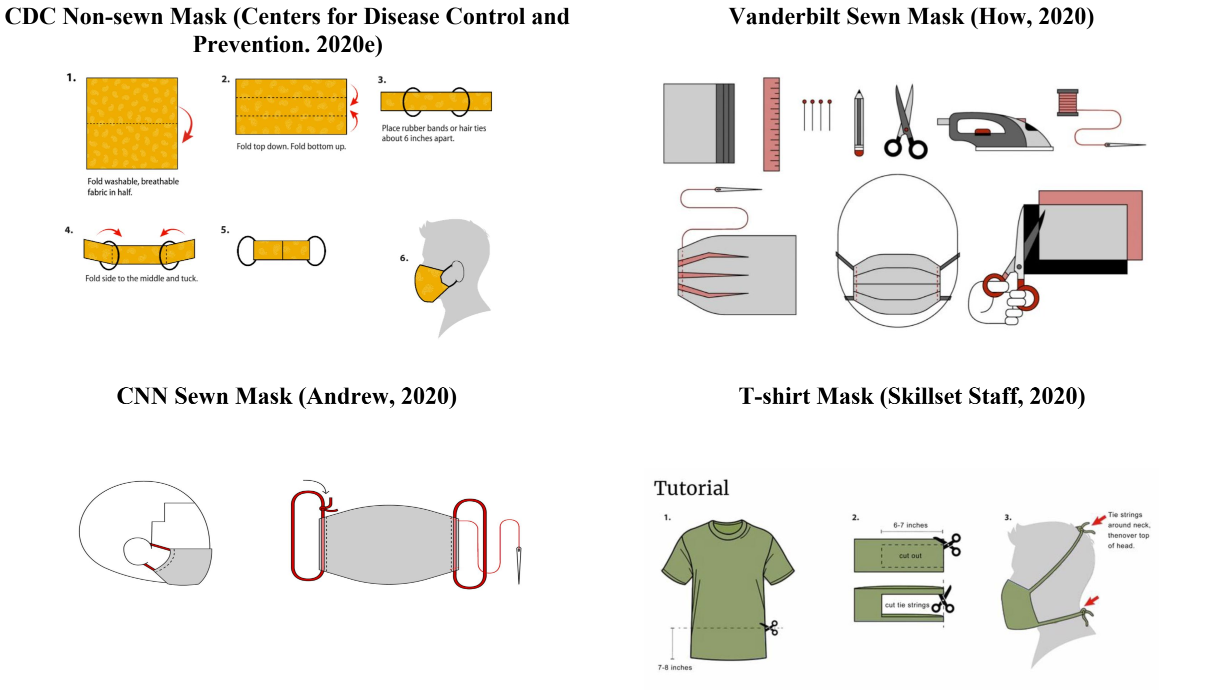


Figure 1. The above figure displays the four DIY masks used for benchmarking.

In order to assess the comfort of the DIY masks in Figure 1 above, similar commercially produced masks were found online and customer reviews were benchmarked. These commercially produced masks can be found in Figure 2 (page 7) below. Mask reviews were sorted and analyzed in order to see what users liked the most and the least from the masks, specifically in regards to the comfort. The first mask is the Disposable Filter Mask. This mask is similar to a surgical mask. Overall, when asked about comfortability, 83% of reviewers stated specifically that the mask was comfortable. This was due to the thin and soft fabric. When the fit was mentioned, 40% of the reviews stated that the mask had a poor fit due to the design of the mask and the placement of the ear straps (Eventools Official, 2020). The second mask that was analyzed was the Washable and Reusable Cotton Mask. This mask is very similar to the sewn mask that is recommended by the CDC but uses different materials for the mask. Overall, 83% of the reviews mentioned that the mask was comfortable. This factor was primarily due to the spun-bonded cotton fabric used and the usage of an O ring in order to make the ear loops adjustable. When fit was mentioned, 38% of users stated that the fit was poor. This was due to sizing issues for different faces. When the reviews discussed how aesthetically pleasing the mask was, 100% of the reviews were positive, stating that the design was the main factor in this decision (UTRIPSUNEW, 2020). The final mask looked at was the Outdoor Sport Mask. This mask is most similar to the T-Shirt Mask, as there is only one thin layer of continuous, non sewn fabric (Skillset Staff, 2020). When comfortability was discussed in the reviews, 70% of users stated that the mask was comfortable on their face. This was primarily due to the use of cotton for the mask, and the use of one layer. However, when it came to the ear straps, 40% of people said that they were uncomfortable. This poor review was due to the fact that the mask was smaller in the ear area and the material dug into the user's ears, sometimes causing the ears to be pulled forward (Ruphance Store, 2020). Overall, this analysis of reviews informed the team that the stakeholder requirement regarding comfort should be of higher importance and allowed the team to understand that ear loops, material type, and overall size of the mask were very important pieces to consider when designing the mask.

Disposable Filter Mask (Eventools Official. 2020)

Washable and Reusable Cotton Mask (UTRIPSUNEW. 2020)

Outdoor Sport Mask (Ruphance Store. 2020)

Figure 2. The figure above shows the three masks from Amazon that were used to gain more insight into the comfortability requirement.

Another important article for determining benchmarks for the mask was a study by the American Chemical Society (ACS), "Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Masks" (Konda, 2020). In this article, various fabrics were tested for their filtration efficiency, or the percentage of aerosol particles that they were able to filter. This data was used as a benchmark for the desired filtration efficiency of the DIY mask design. However, as pointed out by the article itself, the idea of fit was not considered when testing the materials, and an improper fit could decrease the filtration efficiency of a mask by up to 60%. Another limitation of the article is that it did not consider how masks could degrade in filtration efficiency from washing and decontamination.

To address the question on how to evaluate the fit of masks, an article by the Disaster Medicine and Public Health Preparedness journal was considered (Davies, 2013). In the article, which was published in 2013, researchers defined a method of determining how well masks fit, which they called the "fit factor." The fit factor was defined as the ratio of the concentration of outside particles compared to the concentration of particles inside the mask that leaked inside after a set period of time. These fit factors that were found for various homemade masks, mostly in the range of 1.5-2 were used to determine a benchmark for the DIY mask design. However, it should be noted that the context for their experiment was for blocking influenza, and they also did not consider the degradation of mask quality from washing and decontaminating. Both influenza and coronavirus are respiratory diseases, but much more is known about the transmission of influenza. Influenza virus particles are typically the same size as coronavirus particles, but coronavirus particles can, on occasion, be as small as 50 nm while the smallest influenza particles are around 80 nm (Vajda, 2016).

To address the topic of comfort, two articles were considered. The first was a chapter from The Textile Institute Book Series titled "Advanced Characterization and Testing of Textiles," (Classen, 2020) where various comfort testing metrics and methods were described. However, the tests listed utilized proprietary machines that would be difficult and expensive to obtain. So instead of the comfort benchmark, the article "Comparison of Facemask Characteristics With User Assessment of Comfort" published by the University of Iowa was considered (Purdy, 2019). In the study, N95 respirators were evaluated through a Likert scale from 1 to 6 on various comfort factors such as fit, temperature, and ease of breathing. While this scale was approved by their institutional review board, it was only conducted on the University of Iowa students and not people in low resource settings as desired for this project. It is important to recognize that different cultures have different interpretations of comfort, and therefore would likely interpret the Likert scale differently. Due to time and safety constraints, input regarding comfort from people in low resource settings throughout the world was not acquired. For an accurate comfort survey to be administered, the results need to be interpreted through the lens of different low resource regions.

Stakeholders and Experts

To develop requirements and determine a need for the project, several stakeholders and experts were identified and consulted. Table 1 below contains descriptions of the various engagement levels with stakeholders. Additionally, Table 2 (page 9) contains a current list of identified stakeholders, the level of engagement with the stakeholder, and the corresponding information gathered. Table 3 (page 10) contains a list of identified experts, the level of engagement with each expert, and the corresponding information gathered. Experts are defined as contacts who have extensive knowledge regarding various aspects of the project but may not have a stake in the outcome of the project.

Table 1. The following table contains the different levels of stakeholder engagement and their corresponding descriptions.

ENGAGEMENT LEVEL	DESCRIPTION
Constant contact	Identifies stakeholders that are consulted with on a minimum biweekly basis.
Have engaged	Identifies stakeholders that have been consulted with and interviewed at least once at this point in the project.
Used as resource	Identifies stakeholders that are not feasible to meet with but have been used as a literature and benchmarking source.

Table 2. The following table contains a list of stakeholders and the respective engagement level and information gathered. See Table 1 above (page 8) for the description of the various engagement levels.

STAKEHOLDER	ENGAGEMENT LEVEL	INFORMATION GATHERED
Caroline Soyars	Constant contact	Caroline provided connections to contacts in Ghana and at the university. She also gave feedback and expertise regarding requirements and their corresponding specifications.
People who live in low resource settings	Have engaged	Two community members in Ghana, named Ama and Afia, provided information regarding mask creation and cost estimates in Ghana. Their specific contributions are outlined in Table 3 among other experts.
University students and their families	Have engaged	A pilot survey has been sent to both close friends who are university students and family members to determine the priority of mask comfort and different metrics of comfort. The survey will be sent to a larger university audience once verified by CSCAR or the SRC. A subset of this stakeholder group will also be used to safely try prototypes and assess comfort.
Professor Aubree Gordon	Have engaged	Professor Gordon provided expertise on public health in low resource settings through her extensive work in Nicaragua and helped the team decide to focus on DIY mask creation over N95 respirator decontamination.
University of Michigan (ME450)	Constant contact	The university and ME 450 class have provided funding, potential resources, connections, and learning modules to enhance the project.
Center for Disease Control and Prevention (CDC)	Used as resource	The CDC provided useful benchmarking information regarding making DIY masks in the US.
World Health Organization (WHO)	Used as resource	The WHO provided benchmarking information regarding the state of COVID-19 in the world.

Table 3. The following table contains a list of experts that have been consulted and the respective engagement level and information gathered. Both subject matter experts and local area experts are included. See Table 1 (page 8) above for the description of the various engagement levels.

EXPERT	ENGAGEMENT LEVEL	INFORMATION GATHERED
Professor Kathleen Sienko	Constant contact	Professor Sienko has provided continuous guidance on project progress and scope, stakeholder connections, and requirements.
Kwame Nkrumah University of Science and Technology (KNUST) Student Team	Have engaged	The KNUST student team has provided insight into the state of COVID-19 in Ghana, local mask-wearing culture, available materials for DIY masks, and information regarding existing DIY mask washing procedures.
Professor Herek Clack	Have engaged	Professor Clack described the testing apparatus he helped construct that tests the filtration efficiency of masks. He also informed the team on the various studies conducted by the university in 2020 since the start of the COVID-19 pandemic. He also provided a connection to Professor Gamba.
Professor Andre Boehman	Have engaged	Professor Boehman shared knowledge regarding current testing at the University of Michigan regarding modeling the spread of COVID-19 with aerosols. He provided a connection to Professor Clack and offered to share testing equipment (e.g. SMPS).
Professor Mirko Gamba	Have engaged	Professor Gamba provided access to his laboratory and his testing apparatus that can test the filtration efficiency of masks and fabric swatches.
Ama and Afia	Have engaged	Ama and Afia are both community members in Kumasi, Ghana who sews masks and work in textiles for their community. Ama shared information regarding the materials she uses, how long it takes her to make each mask, and how much is costs to make each mask. Afia shared information regarding the cost of specific fabrics like silk and cotton to aid in the cost analysis.

Requirements & Specifications

In order to create a design that accurately meets the stakeholders' needs, requirements and specifications were developed. Table 4 below contains the project's stakeholder requirements, engineering specifications, priority level, and the corresponding sources used to verify the need for the requirement and the specification. The priority level for each requirement was implicitly confirmed through meetings with stakeholders and literature related to the project.

Table 4. The following table contains the stakeholder requirements for the project along with the corresponding engineering specification and priority level.

PRIORITY	STAKEHOLDER REQUIREMENTS	ENGINEERING SPECIFICATIONS
High	Is Low Cost	1 mask costs ≤ 2 cedis ($0.34 USD)
High	Minimizes Air Flow Around Edge of Mask	Fit factor, the ratio of particle concentration outside of the mask versus inside the mask after a set testing period, should be ≥ 2
High	Has Good Filtration Efficiency	Filtration efficiency ≥ 50% for particles ≥ 50 nm in size
High	Uses Available Materials	Available materials constitute common household materials (e.g. cotton, silk, nylon, chiffon, flannel)
High	Is Comfortable to Wear	Likert score > 4 (scale 1-6) for each of the three metrics: comfortable fit to face, temperature, and ease of breathing
Medium	Has a Long Lifetime*	Can sustain > 20 uses - 1 use is specified as any amount of time the mask is worn from when it is put on to when it is taken off if one comes within 6 feet of another person - 1 wash occurs after each use and constitutes soaking and scrubbing the mask by hand in tepid water with laundry detergent and leaving the mask out in the sun until dry *Lifetime is an active area of exploration. There is currently limited research on this topic.
Medium	Is Easy to Create by General Population	Can be made in ≤ 30 minutes Can be made in ≤ 12 steps

Originally, using the CDC's template for a DIY mask, the cost to produce such a mask was calculated by looking at the materials needed. The CDC's non-sewn mask requires 20" x 20" rectangles of cotton fabric and two rubber bands or hair ties to be created. The final cost of the materials comes out to be $1.56 USD per mask, and might be more expensive than a sewn option due to the large amount of fabric used (Centers for Disease Control and Prevention, 2020e; Walmart, 2020; Bound Tree, 2020). However, upon connecting with a new stakeholder in Ghana, Ama, who makes masks for her community, it was determined that the average DIY mask costs approximately 2 cedis, or $0.34 USD. Therefore, the cost specification was set at less than or equal to 2 cedis (Ama, 2020). It is important to note that the cost of living in Ghana is lower than that of the United States, so materials cost more and have to be scaled down to determine whether or not this specification is met. Low cost was determined to be a high priority because the target demographic of the project is people who live in low resource settings. Additionally, the low-cost requirement was directly included in the initial project description (ME 450, 2020).

When initially determining the specifications regarding fit, literature by the Society for Disaster Medicine and Public Health was used (Davies, 2013). The mask's fit was tested using a Model 8095 N95-Companion Mask Fit Tester and TSI PortaCount Plus Respirator Fit Tester, which measure the total concentration of particles both outside and inside the mask after being worn by a user for seven consecutive exercises each being 96 seconds in duration (Davies, 2013). The ratio of particle concentration outside to particle concentration inside constitutes the fit factor. Literature showed the average fit factor for most DIY masks to be approximately equal to 2 (Davies, 2013).

Filtration efficiency is defined as the percentage of particles blocked by the mask. Literature showed that the average amount of Bacteriophage MS2 particles filtered out by various DIY masks, or filtration efficiency, was 50.85% if they were made using 100% cotton T-shirts. Masks with a cotton mix had a filtration efficiency of 70.24% while surgical masks had a filtration efficiency of 89.52% (Davies, 2013). Since coronavirus particles have been known to be as small as 50 nm, the design must be able to filter out particles of this size (Advances, 2006). The size of Bacteriophage MS2 particles is usually 23 nm in diameter, meaning that the filtration efficiency of the materials in this study is most likely higher for coronavirus particles due to the particles' larger size. With that being said, the specified target has been set to a filtration efficiency of 50% since this is the average performance of DIY masks in the study. If the mask design were to have an efficiency of less than 50%, there would be no reason to use it compared to the alternative options already available, rendering it ineffective. The filtration efficiency requirement was deemed as a high priority because the mask needs to be effective in filtering out coronavirus particles to serve its purpose of keeping people from getting sick. The importance of filtration efficiency was also stressed while interviewing both Professor Boehman and Professor Gordon (Andre, 2020; Aubree, 2020).

To specify available materials, both a literature search and interview with the KNUST Student Team in Ghana were conducted. The KNUST team was asked about materials typically used in DIY masks in Ghana. This interview, along with analyzing literature regarding materials common to low resource settings, led to the development of a consistently expanding list of materials to test (Schive, 2020; University of Arizona, 2020; Konda, 2020; KNUST Team, 2020). Using available materials was classified as a high priority requirement for the same reason that low-cost was deemed a high priority. If the materials used to make the DIY mask are not available, the design will likely not be used, causing the project to fail.

When creating specifications for comfort, literature written by the University of Iowa was found that created a Likert scale with a range from 1 to 6 which assessed three different comfort metrics: fit to face, temperature, and ease of breathing. Masks were sent to students along with a form that had them rank the comfort metrics. An average Likert score of 4 was recorded for N95 respirators (Purdy, 2019). This led to a specified comfort rating greater than 4 for each of the three metrics. Unfortunately, the Likert scale created by this study is limited due to the subjects being limited to only students, and the study only covers three metrics of comfort despite there being other potential metrics like sweat build-up and tightness. The comfort requirement is currently set as a high priority. Upon sending out a Comfort Priority Survey to university students, alumni, family members, and contacts in Ghana, it was found that different metrics of comfort are valued almost as much as the effectiveness of the mask at protecting one from COVID-19, causing the priority level to be adjusted to high priority. More information regarding the Comfort Priority Survey and its results are located in the Engineering Analysis section (pages 28-30). It is recognized that there are different cultural norms regarding comfort. In this semester, the team's ability to assess the mask's comfort with different cultures was limited due to time constraints and the current state of the pandemic. For safety, the team instead asked friends and family about mask comfort. Once the pandemic is under more control, reaching out to different cultures is recommended to get a better grasp of the mask's comfort level.

Literature regarding lifetime explained that the average DIY mask could be used approximately 20 times when decontaminated with methods such as vaporized hydrogen peroxide and dry heat between each use (Oh, 2020; Centers for Disease Control and Prevention, 2020f). Therefore, the specification for the mask's lifetime was set to 20 uses. The specification also shows that handwashing will be used as an alternative method of decontamination. Hand washing was decided to be the main method of decontamination based on literature and an interview with the KNUST team, in which hand washing in tepid water was described as the current method of decontaminating DIY masks in Ghana (Centers for Disease Control, 2020e; KNUST Team, 2020). Being able to use a DIY mask repeatedly is essential because each DIY mask replacement will cost more money, directly contradicting the low-cost requirement. Instructions will be added that recommend the user to only use the mask 20 times. However, the team acknowledges that it has little control over the user and what they do with the product. Due to a lack of literature regarding mask lifetime, this specification is an ongoing area of exploration and is therefore regarded as a medium priority.

The specification for the DIY mask being easy to create by the general public was developed by studying multiple DIY mask tutorials. In those tutorials, the average creation time was approximately 30 minutes. Additionally, mask creation processes ranged from 4 to 12 steps in length. This resulted in a specified creation time of fewer than 30 minutes with less than 12 steps (Centers for Disease Control and Prevention, 2020e; Gierthmuehlen, 2020; Khong, 2020). Ease of creation by the general population was determined to be of medium priority because it ultimately does not impact the price of the mask or the mask's ability to protect against coronavirus. However, a DIY mask that is harder to make is less likely to be adopted by the general public.

Additional design considerations not listed above that are relevant to the project include the different situations in which people use masks and how long people typically wear the mask during each use. Some individuals may wear a mask for only 1-2 hours when taking care of errands outside. However, some individuals may have to wear a mask for 8+ hours in an office building for work. In order to create a mask that can be used for all kinds of situations and lengths of time, these factors are being considered during the design process. Another design consideration not listed above is sewing co-ops. While the target creators are members of the general population, it is important to acknowledge that there are sewing co-ops with skilled workers in places such as Ghana who may be able to make masks faster than most people. These co-ops can allow for more complex mask designs, but there is not much information online regarding these co-ops aside from a few news articles (In, 2020; Knott, 2020; Winsor, 2020). Due to a lack of literature regarding these co-ops, this consideration is recommended to be further explored.

CONCEPT EXPLORATION

With the defined requirements and specifications established, concepts were created by the team and further developed into potential designs. Potential designs were then refined and ranked to determine which should be testing with various engineering analyses.

Concept Generation & Development

To generate many different concepts and potential solutions to the problem guiding this project, three different concept generation techniques were used: brainstorming, design heuristics, and morphological analysis.

Brainstorming is the process of generating ideas within a group (Zenios, 2009). This skill is useful for exploring initial possibilities, and has the following rules: defer judgement, encourage wild ideas, go for quantity, and be visual. While there are many ways to go about brainstorming, these main rules were focused on, and during a full team meeting, time was spent generating as many ideas as possible. The "no wrong idea" mentality allowed for a positive space where one could say anything that comes to mind, while visuals were used to map out and further imagine concepts. Brainstorming encouraged the rapid production of a diverging solution space. Various concepts were generated in the brainstorming session through the creation of a mind map. No ideas were evaluated during the brainstorming session, so the ideas on the mind map may very well not be feasible. The mind map is shown in Figure A.1 in Appendix A (page 52).

In addition to creating the mind map, design heuristics were also considered to help generate out-of-the-box ideas. Design heuristics is an experimentally driven design tool that looks to establish innovative ideas (Christian, 2012). This tool aids in idea generation and helps to make multiple decisions. Design heuristics does not aim to determine a single solution (Christian, 2012). The set of 77 design heuristics defined by Design Heuristics, LLC allowed for high-level abstractions of solutions to be made. Of the 77 heuristics, 31 of them were considered, as many redundancies were found and certain heuristics were outside the scope of the project. It was found that design heuristics was most successful in diverging high-level concepts and that it made the team think outside the box. The notes taken when working through the design heuristics are located in Figures A.2 through A.7 in Appendix A (pages 52-55). This new path to augment a possible design was proven useful in order to rapidly diverge the team's solution space. As this solution space increased, so did redundancies. These redundancies signified to the team that there were enough ideas generated to work with and that converging these ideas could soon begin.

The final tool used during concept generation and development was morphological analysis. Morphological analysis typically takes the form of a matrix and is a way to generate ideas analytically and methodically (Morphological, 2020). In this chart, possible outcomes were listed on the basis of their functions or the category they fall within. The functions and categories were then placed in the columns, and components, which are the ways that the function is solved, were placed in the rows. The group's morphological analysis chart can be seen in Figure A.8 in Appendix A (page 56). During this third meeting, ideas previously generated were compiled and then categorized. These categories allowed for a greater number of full concept designs to be produced, leading to further divergence of ideas.

The next step in the concept exploration process was to combine the various ideas generated into different DIY mask designs. In order to do this, the team split up and each person created two or three designs using the mind map from brainstorming, the notes from design heuristics, and the morphological chart.

The team generated a total of eleven full mask designs. The two designs not shown in the body of the report are located in Figure A.9 in Appendix A (page 57).

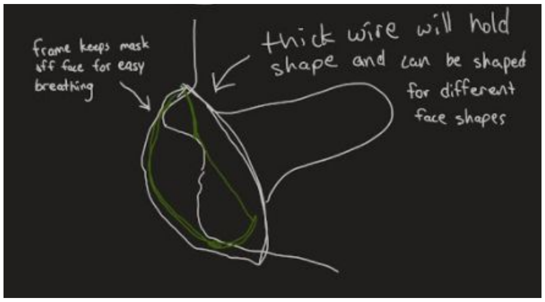
There were multiple ways to know that an adequate amount of ideas had been generated. As concept generation progressed, it became increasingly difficult to generate unique ideas. Additionally, the initial goals that were set for ideas and concept designs were met. Table 5 below displays the target number and the actual number of ideas and full solution concepts that were generated throughout the concept exploration and development process.

Table 5. The following table shows the target number and the actual number of concepts generated from concept generation.

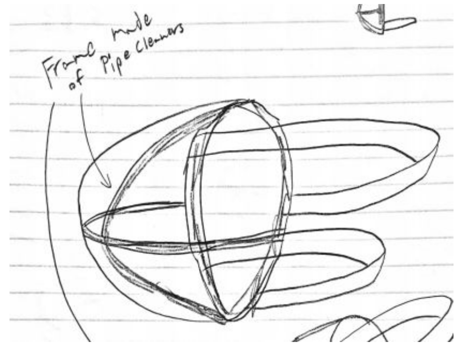
CONCEPT GENERATION DASHBOARD	TARGET NUMBER	ACTUAL NUMBER GENERATED
Number of Ideas	60	71
Number of Full Concept Designs	10	11

As full concept designs were being developed by team members individually, some of the ideas generated had repetitive features. Figure 3 (page 16) below contains four of the eleven full designs that were created by three different team members individually. Wire Frame Mask and Wire Frame Mask 2 were both very similar, with each having elastic around the ears, wire support over the nose, and a wire frame between layers of fabric to keep the mask elevated off of the face for increased comfort. Adhesive Mask and Body Tape Mask were also very similar to one another, with a wire support over the nose and an adhesive or tape that would stick the mask to the face. Both the number of ideas generated and the redundant designs created separately by different team members prove that the solution space was sufficiently explored.

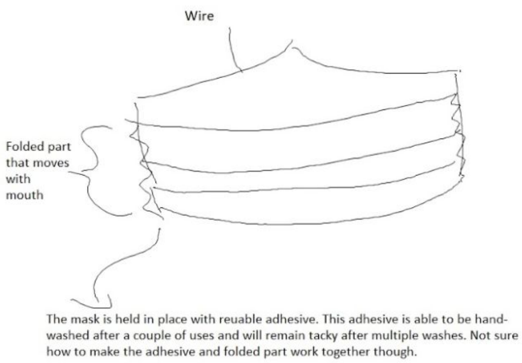
Wire Frame Mask



Wire Frame Mask 2



Adhesive Mask



Body Tape Mask

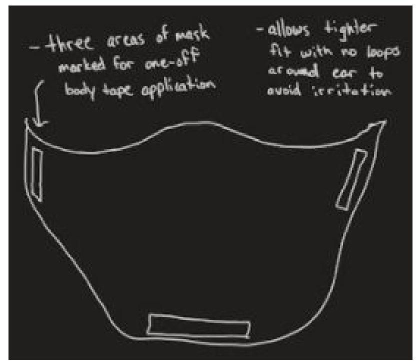


Figure 3. The figure above shows four of the designs made during the concept generation and development process. The similarities between the two wireframe masks and the two adhesive/body tape masks show redundancy in the solution space and therefore help prove a complete solution space.

Concept Evaluation & Selection

In order to evaluate the generated concepts and select possible solutions for testing, a decision matrix was created. First, the criteria for the decision matrix were established based on the stakeholder requirements. These criteria were then weighted according to the respective requirement priority, with a weight of 3 being applied to high priority requirements, a weight of 2 being applied to medium priority requirements, and a weight of 1 being applied to low priority requirements. These weights were established based on initial requirement priority. Priority of the comfort requirement was updated later upon conducting the Comfort Priority Survey. The "lifetime" requirement was split into two criteria: durability and lifetime. This was done so that masks could be evaluated based on their durability and their number of expected uses. Table 6 (page 17) below shows each of the criteria and their respective weights.

Table 6. The table below contains the criteria for the decision matrix established based on the stakeholder requirements and their associated weights.

CRITERIA	WEIGHT
Suspected Fit	3
Accessible Materials	3
Suspected Comfort	2
Simplicity	2
Durability	2
Lifetime	2

Stakeholder requirements regarding the low cost and the filtration efficiency of the masks were not included in this decision matrix. This is due to the fact that cost estimates can be included within the accessible materials criteria. Additionally, material filtration efficiency was studied separately from the structure of the mask. For the most part, any of the generated mask designs can be made with any combination of fabrics to filter out particles.

A scale used to rate each concept in the decision matrix was established based on existing solutions discovered through benchmarking. Existing solutions were identified to provide an example of what each rating would look like for each criteria. This allowed for a more uniform evaluation process, as each design was compared against the same baselines for each criteria. Table 7 below shows the scale and examples that fit each rating for each of the criteria. Ratings without examples represent gaps in existing solutions. Additionally, the lifetime criteria ratings were specified by the expected number of uses.

Table 7. The following table contains the scale used to rate the different concepts in the solution matrix along with examples of existing solutions that represent each rating. The lifetime criteria ratings were specified by the expected number of uses.

	1	**2**	**3**	**4**	**5**
SCALE	**Very Bad**	**Bad**	**Neutral**	**Good**	**Very Good**
Suspected Fit	CDC folded mask	Cloth mask w/ no structure	Surgical mask		N95 respirator
Accessible Materials	Irregular/uncommon fabrics		Available materials	Repurposed materials (i.e. t-shirt)	Natural materials
Suspected Comfort	N95 respirator	Surgical mask	Cloth mask w/ structure	Cloth mask w/ no structure	No mask
Simplicity	N95 respirator	Complex sewn mask	Sewn CDC mask	One-piece cloth mask	Folded CDC mask
Durability	Folded mask		Surgical mask		N95 respirator
Lifetime	1	5	10	15	20

With the criteria, weights, and scale established, a meeting was held with the entire team where each design concept was discussed one-by-one for each criteria, and then rating was chosen by the team. Figure 4 below contains the decision matrix populated with ratings.

Concept	Suspected Fit (3)	Accessible Materials (3)	Suspected Comfort (2)	Simplicity (2)	Durability (2)	Lifetime (2)	Aggregated Score
Combined Fabric & Nylon Mask	4	3	4	3	3	3	**47**
Modified Gaiter	3	3	3	3	4	4	**46**
Separate Fabric & Nylon Mask	4	3	2	3	3	3	**43**
Modified Sewn Mask	3	3	3	3	3	3	**42**
Cone Mask	3	3	3	3	3	3	**42**
Modified Folded Mask	2	3	2	5	1	5	**41**
Wire Frame Mask	3	3	3	2	3	3	**40**
Wire Frame Mask 2	3	3	3	2	3	2	**38**
Snap Layer Mask	3	1	3	2	3	3	**34**
Body Tape Mask	4	1	2	3	1	1	**29**
Adhesive Mask	4	1	2	3	1	1	**29**

Figure 4. The following table contains the decision matrix used to evaluate the concepts generated for the project.

The aggregated score for each concept was calculated by doing a weighted sum across all of the criteria for a respective concept. The design with the highest score, Combined Fabric and Nylon Mask, is listed at the top and is highlighted in green. The four runner-up concepts are highlighted in yellow. Figure 5 below shows concept sketches of the four runner-up designs: Modified Gaiter, Separate Fabric and Nylon Mask, Modified Sewn Mask, and Cone Mask.

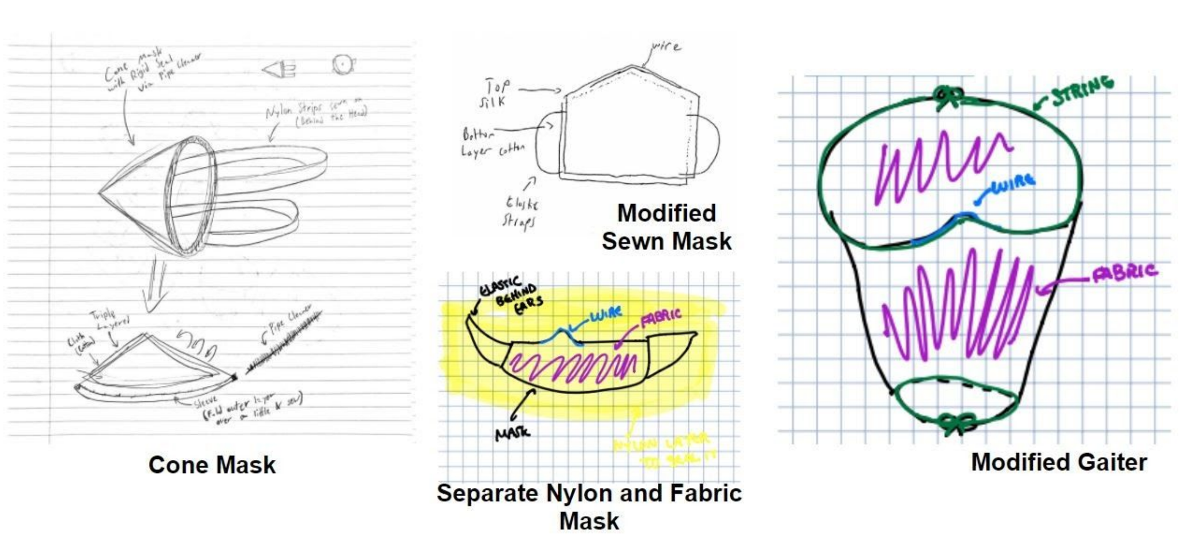


Figure 5. The above figure contains the 4 runner-up designs from concept evaluation and selection. These designs are the Cone Mask (left), Modified Sewn Mask (middle-top), Separate Nylon and Fabric Mask (middle-bottom), and Modified Gaiter (right).

The Cone Mask is created by forming a cloth cone with multiple layers inside of it. A wire is inserted into the base to give the mask a bit of structure and to mold it properly to the person's face. The mask is attached to the user's face using nylon strips that wrap around the head. The cone mask is unique in that its structure allows for the mask to stay off the face, not pressing upon the nose or mouth. It also is wrapped around the head, reducing the amount of pressure on ears caused by elastic ear straps. However, this construction may be difficult due to the 3-dimensional design.

The Modified Sewn Mask is created by taking a cloth layer and sewing a silk layer on top of the mask. A piece of wire is inserted as a nosepiece for a better fit, and the elastic straps wrap around the ears to hold the mask in place. The modified sewn mask is based on the DIY mask recommended by the CDC, making it a reliable choice for the general public to use (Centers for Disease Control and Prevention, 2020e). This reliability does come with flaws since the mask is not very easy to create and could potentially have sizing issues as one speaks.

The Separate Nylon and Fabric Mask is a fabric mask with a wire nose piece on the inside, attached to the face through elastic straps wrapped around the ears. A second nylon layer is then applied over the entire mask to provide a tighter fit and an extra layer of filtration. The Separate Nylon and Fabric mask sports a modular design that allows users to remove a layer for activities such as running outside or walking in low-density areas, providing minor protection without hampering the user's breathing or comfort. Unfortunately, this design's tight fit around the face and ears due to the double layering may cause discomfort. There is also risk involved with allowing a layer to be removed, as it could reduce the amount of protection from COVID-19.

The Modified Gaiter is similar in design to a traditional neck gaiter, but it has a wire above the nose and an adjustable string around the head and neck areas to better fit the user's face. These additions reduce the air flow around the top and bottom edges of the gaiter. This design also has extra layers to make its filtration efficiency much higher than a normal gaiter. The Modified Gaiter scored well in most categories and could be effective for those with facial hair, but tying the mask around the head, neck, and ears could be uncomfortable for certain individuals.

The concept that scores highest on the decision matrix was the Combined Fabric and Nylon Mask due to its success in addressing the most stakeholder requirements. Figure 6 (page 20) below shows a concept sketch of the mask.

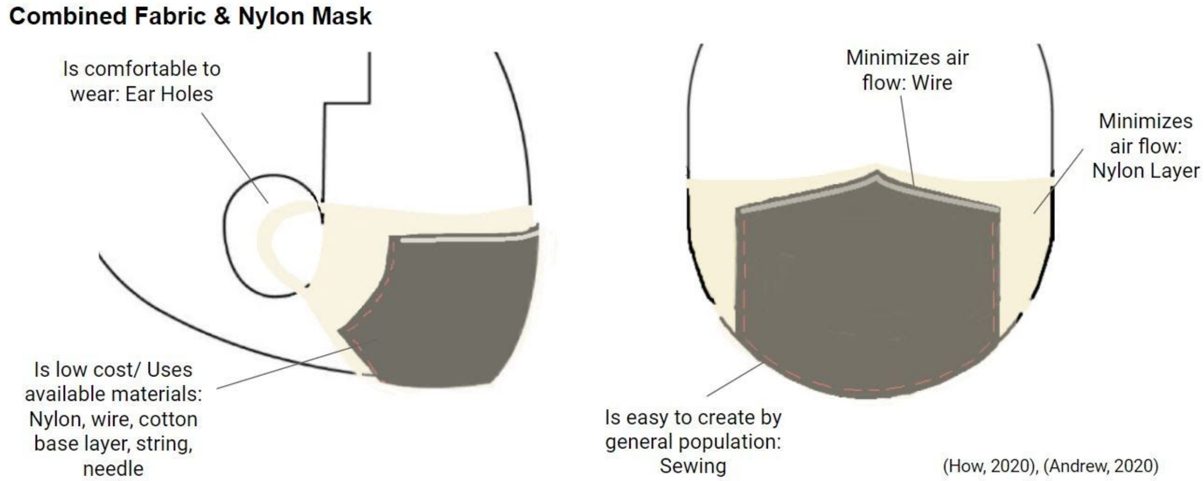


Figure 6. The above figure contains a sketch of the Combined Fabric and Nylon Mask, which scored highest in the decision matrix.

The Combined Fabric and Nylon Mask scored better than all of the other designs because it successfully addresses each of the stakeholder requirements. The mask will be made using nylon and other materials which will work in combination to create a layer that is most effective at filtering out particles. This layer will be identified using the Mask Filtration Efficiency Test described in the Engineering Analysis section. Nylon has been identified as both an available and inexpensive material in Ghana (KNUST Team, 2020), therefore satisfying both the available materials and low-cost requirements. Additionally, the needle and thread required for sewing are very inexpensive and easily accessible. The only material that may have trouble in terms of both cost and accessibility is the wire for the nose support, but any malleable wire or pipe cleaner would be suitable.

Both the wire over the nose and the nylon layer directly address the "minimizes air flow around edge of mask" requirement. The nose wire can be bent and shaped to match the ridge of the nose to eliminate gaps that air would flow through. The nylon layer would then take care of sealing any other potential gaps due to its form-fitting material properties. However, there are many different types of nylon with many different thicknesses and form-fitting behaviors, so the proper nylon needed to be identified and certified as available.

The combination of nylon in addition to the material later chosen to act as the filtering layers both make for a mask that is most likely to successfully address the "has good filtration efficiency" requirement. However, the status of this mask's ability to address this requirement relies on testing regarding the filtration efficiency of possible materials.

In terms of durability and lifetime, the Combined Fabric and Nylon Mask is very sturdy compared to the other generated designs. The absence of an elastic material used for sewn-on ear straps eliminates a potential source of failure. Using nylon to connect to the ears has the potential to be much more durable depending on the thickness of the nylon. Additionally, the increased number of layers makes the mask less likely to tear. While further testing is required to determine how the materials react to different numbers of uses, there is no evidence to suggest that this material would be limited to less than 20 uses.

Compared to the other concepts, this preliminary solution does not appear to be much more difficult to create than a traditional CDC sewn mask. The absence of elastic ear straps makes the sewing process less intricate. Additionally, sewing the filtration layers onto the nylon does not require advanced sewing skills. The wire over the nose is the most intricate part of the mask but can be done by wrapping it in a layer of fabric and sewing the wrap shut and then folding the ends of the wire so they don't stick through or tear the fabric. While prototyping, the simplicity of the mask as well as the number of steps required for creation was recorded during the Mask Fabrication Test.

Lastly, the Combined Fabric and Nylon Mask addresses the "is comfortable to wear" requirement, as nylon has been found in literature to be a comfortable material (Bhattacharjee, 2020). This comfort was further verified later by the Mask Comfort Test. Potential points of discomfort include potential sweat build-up under the mask and breathability issues caused by an increased number of layers. Additionally, if the wire over the nose is not concealed correctly, it could potentially poke at the skin and cause irritation. Stitches and seams in the sewing may also cause skin irritation depending on their location on the face.

Overall, this mask addresses all stakeholder requirements. This design, along with two other selected designs, were later prototyped and tested.

SOLUTION DEVELOPMENT & VERIFICATION

To further refine the list of designs and determine effective elements of each, prototypes were constructed and tested using various engineering analyses. Once a final design had been selected and modified from those analyses, satisfaction of requirements was verified.

Engineering Analysis

To answer key design drivers, multiple engineering analyses were planned and executed. A list of design drivers can be found in Table 8 (page 22) along with the title of the accompanying engineering analysis that addresses those drivers and the priority level for each design driver. Since each design driver correlates to a stakeholder requirement, design driver priority was determined based on requirement priority. The subsequent section outlines the prototyping process and each engineering analysis, including a detailed description of the analysis and the results.

Table 8. The following table contains the list of engineering analyses and their corresponding design drivers they address. Each design driver also has a corresponding priority level based on stakeholder requirement priority levels.

TEST	DESIGN DRIVERS	PRIORITY
Mask Fabrication Test	How long does it take to make each mask?	Medium
Mask Fit Test	Which mask design minimizes the amount of air flowing around the edge of the mask?	High
	What components of each mask may contribute to better fit?	High
	Where does the most air flow occur?	High
Mask Comfort Test and Comfort Priority Survey	Which mask design is the most comfortable?	Medium
	What about the masks may make them comfortable?	Medium
Mask Filtration Efficiency Test	Which combination of mask materials can filter out the greatest amount of particles?	High
	How does number of uses and washes impact filtration efficiency?	Medium

Prototyping

Due to the fact that most of the engineering analyses are empirical tests, prototypes of three different designs were made. Table A.1 in Appendix A (page 57) shows a list of materials purchased for prototyping and the total cost. Empirical tests were selected as the primary form of engineering analysis due to their simplicity. Since the proposed designs are relatively easy to create within the constraints imposed by the pandemic, empirical tests allow for simple engineering analyses. It is also important to note that each design prototyped was sewn by hand due to the fact that sewing machines may be less common in low resource settings.

The first mask to be prototyped was the Combined Fabric and Nylon Mask, as it was the highest-scoring mask from the decision matrix. This mask required cotton and nylon for construction, along with an aluminum wire for over the nose. First, basic measurements were taken of the width of the face, the distance between the mouth and the back of the ears, and the distance between the bridge of the nose and the tip of the chin. Since prototypes were created primarily for the Mask Fit Test, measurements were made on a standard mannequin head. Then, a section of nylon was cut to those dimensions. Two sections of cotton were then cut to be slightly wider than the mouth and able to reach from the bridge of the nose to the tip of the chin. An inch was added to the longitudinal axis of the cotton to account for some material folding over and enclosing the wire above the nose. The two pieces of cotton were then sewn together to form a double layer using a running stitch (Harshitha, 2020). A piece of aluminum wire was cut to span the width of the cotton fabric. The top of the cotton swatch was folded over the wire and then enclosed using a blanket stitch. Next, the cotton swatch and wire assembly were centered on the nylon fabric and sewn on using a running stitch. Lastly, slits were cut an inch from the side edges of the nylon to act as ear holes. A picture of the Combined Fabric and Nylon Mask, as prototyped, is shown in Figure 7 below.

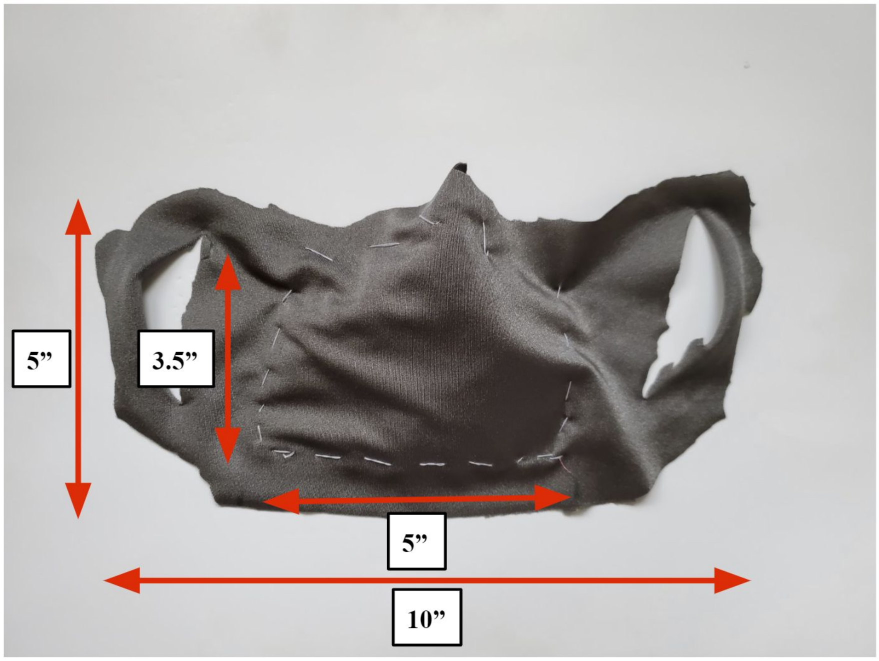


Figure 7. The above figure contains an image of the prototyped Combined Fabric and Nylon Mask with the necessary dimensions shown. The interior dimensions indicate the dimensions of the cotton portion of the mask.

The second concept to be prototyped was the Modified Gaiter. This design was chosen because it was the second-highest scoring concept on the decision matrix. Prototyping began by measuring and cutting two pieces of cotton fabric, each of which was approximately 12 inches by 25 inches. These dimensions were chosen by measuring the approximate distance between the middle of the neck and the bridge of the nose and the approximate circumference of the mannequin head. The two pieces of cotton were sewn together on all edges using a running stitch. Next, both the bottom and top edges (the 25-inch edges) of the cotton were folded to create 1 inch of overlap. A piece of aluminum wire approximately 6 inches in length was cut and placed into the corner of the top fold and was centered on the width of the fabric. A blanket stitch was used to connect the wire to the cotton. The folds on both the top and bottom of the fabric were then sewn shut using a running stitch to create a slot. Two straps of nylon, both 28 inches in length and 1 inch in width, were then guided through the slots by attaching a clothespin to the end and pinching it through. The cotton fabric was then sewn into a cylindrical structure by connecting the two 12 inch sides of the fabric together using an invisible stitch. A picture of the Modified Gaiter, as prototyped, is shown in Figure 8 (page 24) below.

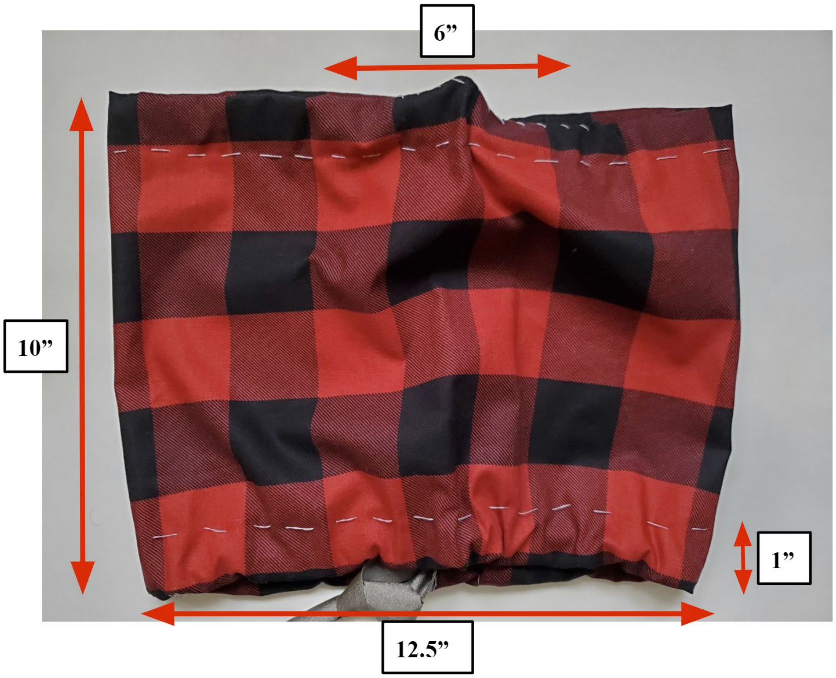


Figure 8. The above figure displays the Modified Gaiter as prototyped with the necessary dimensions. It is important to note that the Modified Gaiter is cylindrical, so the actual width if unsewn is approximately 25 inches.

The final concept to be prototyped was the Wire Frame Mask. Although this mask was not among the highest-scoring in the decision matrix, upon completing the Peer Consulting Activity with the rest of the ME 450 section, it was determined that a design with a way of keeping the mask elevated off of the mouth is desired by a subset of potential end users to achieve proper comfort. Therefore, the Wire Frame Mask was selected as the third concept to be prototyped. First, the width of the mannequin head was measured along with the distance between the bridge of the nose and the tip of the chin. Then, two pieces of cotton fabric were cut to those dimensions, with an inch added to both length and width to account for the desired curvature of the mask. One of the layers was molded around the wire frame and sewn on by pushing the thread through the fabric and wrapping it around the wire. The second piece of cotton fabric was then sewn to the first layer of cotton by using a running stitch on the edges and a running stitch around the location of the wire frame. 7.5-inch long straps were then cut from nylon and attached to the side edges of the mask using a running stitch. Each strap was approximately 0.5 inches in width. A picture of the Wire Frame Mask, as prototyped, is shown in Figure 9 (page 25) below.

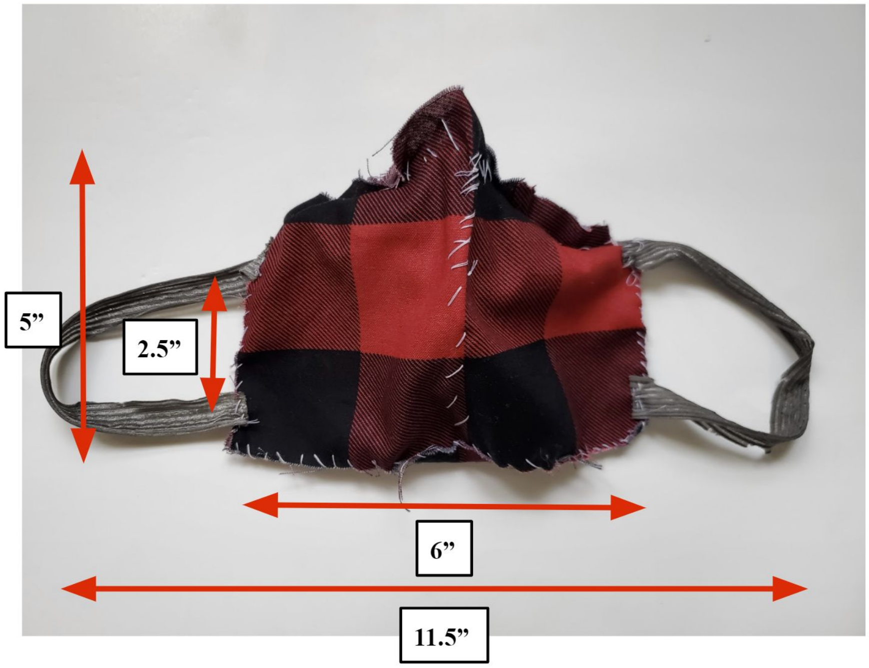


Figure 9. The above figure displays the Wire Frame Mask as prototyped with major dimensions labeled. The wireframe on the inside is not visible.

Mask Fit Test

In order to figure out which mask design minimizes the amount of air flow around the edge of the mask, what components of each mask contribute to a better fit, and where the most air flow occurs from each mask, the team conducted a Mask Fit Test. This test enabled the team to confidently answer the design driver questions previously mentioned and allowed the team to choose what mask design to proceed with while using materials to conduct the test at home. It allowed the team to find which parts of the mask designs were the weakest in terms of allowing air to flow out of the edges. This empirical test was performed by placing the mask prototypes on a mannequin head. A hole was drilled through the back of the head, and a vacuum cleaner blew air through the hole to simulate a constant outward breath. The side profile of the mannequin head with an arrow indicating the direction of air flow through the head is shown in Figure 10 (page 26) below.

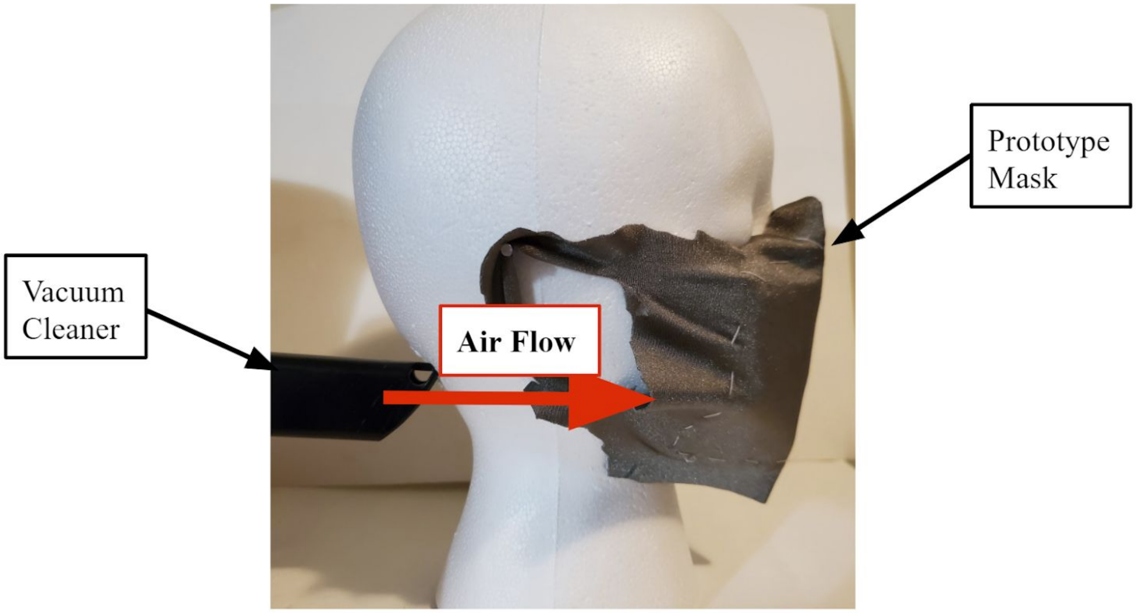
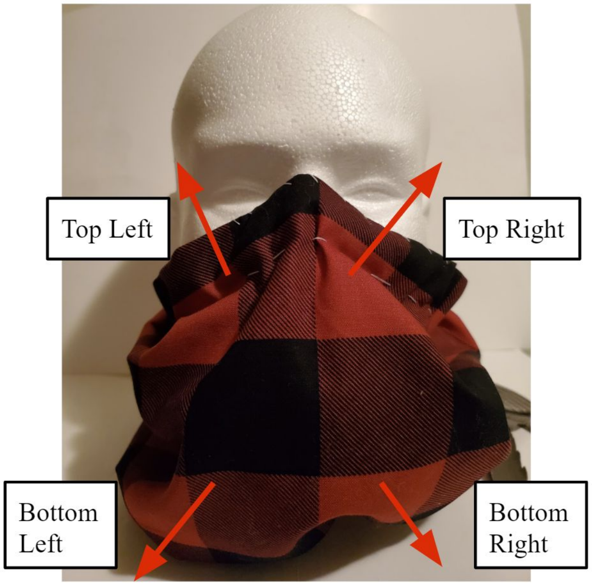


Figure 10. The above figure shows the mannequin head used in the Mask Fit Test along with the vacuum cleaner that simulated an outward breath and a mask being tested.

The vacuum cleaner airspeed was set to simulate the higher range of breath speeds. The airspeed of the vacuum at the end of the mouth was measured to be 10.9 m/s on average during testing, which is slightly higher than the actual speed of a breath of 9.9 m/s (Mhetre, Manisha Rajesh, and Hemant Keshav Abhyankar. 2017). Cling wrap was put inside of the prototypes so all air was forced around the edge of the mask. This cling wrap was extended across the entire interior surface of the mask, blocking all air flow through the mask. Air flow around the edges of the prototypes was then measured using an anemometer. The location where each measurement was taken for both the Combined Fabric and Nylon Mask and the Modified Gaiter are shown in Figure 11 (page 27) below. The same locations were measured for both the Combined Fabric and Nylon Mask and the Wire Frame Mask. The test was repeated three times for each mask, and each mask was taken off of the mannequin head between tests in order to simulate the user donning and removing the mask.

Modified Gaiter



Combined Fabric and Nylon Mask

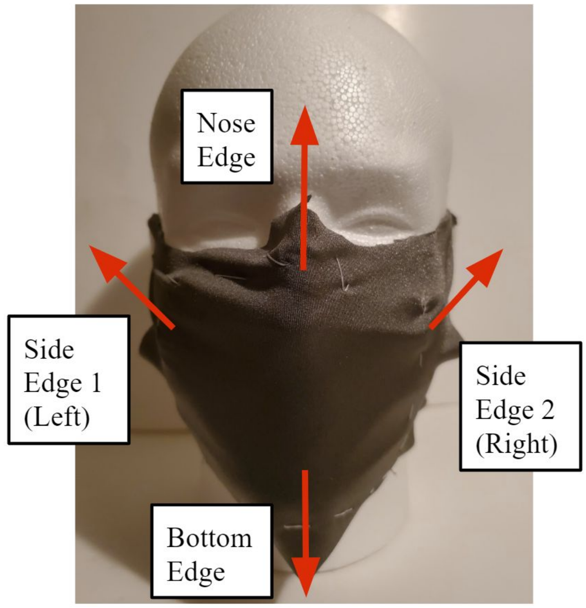


Figure 11. The above figure contains the locations at which measurements were taken for the Modified Gaiter (left) and the Combined Fabric and Nylon Mask (right).

After the mask fit test was performed, it could be seen that all masks let air out through the nose edge. The Combined Fabric and Nylon Mask also let air out through the bottom edge and the Wire Frame Mask let air out through the side edge. The results of the Mask Fit Test for both the Combined Fabric and Nylon Mask and Wire Frame Mask can be seen in Table 9 below. Likewise, the results for the Modified Gaiter can be seen in Table 10.

Table 9. The following table contains the average air speeds measured by the anemometer at each of the four measurement locations for the Combined Fabric and Nylon Mask and Wire Frame Mask.

AVERAGE AIR SPEED ESCAPING [M/S]	BOTTOM EDGE	SIDE EDGE 1 (LEFT)	SIDE EDGE 2 (RIGHT)	NOSE EDGE
COMBINED FABRIC AND NYLON MASK	2.46	0.00	0.00	1.67
WIRE FRAME MASK	0.00	0.60	0.00	2.17

Table 10. The following table contains the average air speeds measured by the anemometer at each of the four measurement locations for the Modified Gaiter.

AVERAGE AIR SPEED ESCAPING [M/S]	TOP LEFT	TOP RIGHT	BOTTOM LEFT	BOTTOM RIGHT
MODIFIED GAITER	0.45	0.55	0.00	0.00

It can be concluded that the wire around the chin of the Wire Frame Mask and the nylon on the sides of the Combined Fabric and Nylon Mask both contributed to better fit. After viewing these results, in order to improve the design of the Combined Fabric and Nylon Mask, a wire will be added around the bottom of the mask in order to improve the fit of the mask.

Since the mask prototypes were made of different materials, cling wrap was placed in the mask to force air out of the sides of the mask. For future testing, it is recommended that the Mask Filtration Efficiency Test be performed before the Mask Fit Test. By ensuring that each prototype has the same filtration fabric, the Mask Fit Test will be able to be conducted without cling wrap, making the analysis more accurate and reliable. Also, for further verification and testing, the fit test done by The Society of Disaster Medicine and Public Health should be conducted (Davies, 2013). This test is described further in the Verification section (pages 38-40).

Comfort Priority Survey

In order to determine how high the general public values various aspects of comfort and the comfort of the mask as a whole, a Comfort Priority Survey was created and distributed. The intention was to further assess the priority of the comfort requirement and to help interpret the results of the Mask Comfort Test, which will be discussed in the next subsection. Additionally, while discovering which aspects of mask comfort are most important to potential users, tradeoffs can be made down the line should they be needed.

Questions for the survey were developed by first outlining the target outcome of the survey. Then, the entire team came together and outlined questions that would potentially meet the intended survey goals. Initially, a rough draft of the survey was made and released to only a select few people, namely friends and family of the team members. The results of this survey indicated a stronger than predicted valuing of comfort in a mask. Thus, the priority of comfort was changed to medium for Design Review 2. Directly following Design Review 2, an appointment was made with a representative from the SRC, the Survey Research Center, to improve the survey for wider release. The feedback from this meeting was taken into account, and the survey was modified with the necessary improvements. A copy of the survey is included in Appendix A (pages 58-60). This new survey was then released to friends and family again, as well as being distributed to the entire ME 450 class.

With over 51 total responses, the new survey provided much more information than the limited release of the first rough draft. The first question of the survey asked participants what type of masks they use. Commercially made fabric masks took the lead with 56%, followed by surgical masks with 24% and DIY masks with 19%. The next question asked participants to rate with a Likert scale from 1-5 how important various aspects of mask performance and comfort were to them. This question provided much less concrete results to interpret, as a generally positive response to the importance of the aspects of masks was seen. It should be noted, however, that the protection of the mask against COVID-19 had the highest average score, followed by "neither too tight nor too loose" and then "does not irritate skin." The lowest scoring aspects were "does not cause sweat build up on face" and "mask is breathable." A pie chart containing the percent of participants who indicated each category as the highest priority is shown in Figure 12 (page 29) below.

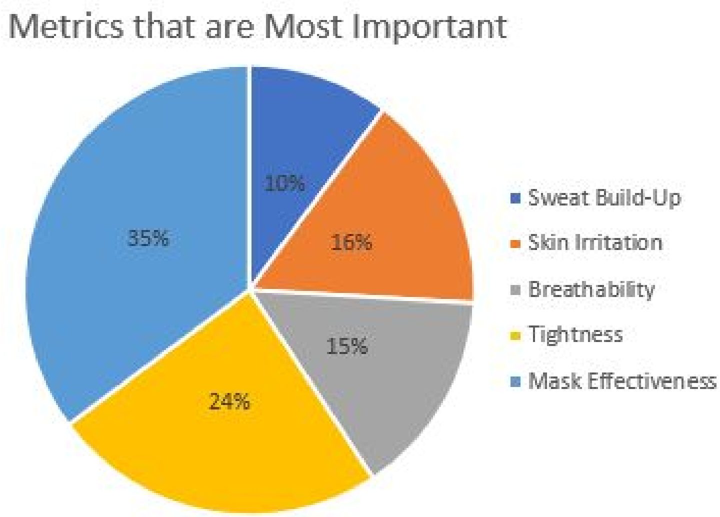


Figure 12. The above figure shows a pie chart indicating the percentage of survey participants that ranked each of the indicated categories as most important.

Participants were then given a free response question that asked which masks they like the least of the ones they have worn, and what about them they dislike. A wide array of answers were received for this question, with some repeating points being about a lack of fit, fogging up in glasses, and being too tight.

It should be noted that while the survey was reviewed by a member of the SRC, it is still not a professional survey. Since all participation was voluntary, some important questions on the survey may have been skipped by participants. With 51 responses, the sample size of the survey is not large, and the population sampled likely does not represent the target population of this project. The many students sampled and the friends and family of the team members represent on average a higher socio-economic status than the targeted low-income areas in the problem description. However, the team decided to still utilize the results, albeit with caution, as it was the best data that could be found on the topic. Following the responses of the survey, the team decided to raise the priority of the comfort specification once more to a high priority.

Mask Comfort Test

As a part of the design selection process, it was important that the comfort of the final few mask designs be considered when selecting a design to move forward with. To this end, a Mask Comfort Test was utilized that would provide insight into how the masks performed comfort-wise.

Following the example set by a study done by the University of Iowa, participants were given several DIY mask prototypes and wore them for a period of 2 minutes. Following this, participants were asked to rate the various aspects of the mask's comfort using a six-point Likert scale, with a score of 1 indicating extreme discomfort and a score of 6 indicating extreme comfort similar to no mask being worn at all. Categories included mask breathability, comfortable fit to face, and temperature (Purdy, 2019). Participants were also asked to rate the three different categories based on how important they perceived them to be. The masks tested included the Combined Fabric and Nylon Mask, the Modified Gaiter, and the Wire Frame Mask. Three people close to the team members were chosen for this test, and after the test, the prototype masks were destroyed.

The mask designs scored relatively similar to each other in regards to comfortable fit to face, but with a few minor differences in the other categories. Most of the masks scored close to a 4 in regards to temperature. The Modified Gaiter scored a 4.5 out of 6 in the fit to face category and had a good breathability score, at around a 5.6. The Combined Fabric and Nylon Mask scored lower in most areas, with scores ranging between 3-4 for all categories. The Wire Frame Mask performed between the Modified Gaiter and the Combined Fabric and Nylon Mask, with a 3.67 in fit, 5 in breathability, and 4.33 in temperature. The results of the final question indicated that breathability was perceived as the most important factor, followed by temperature, and then fit to face. The summary of Likert scores for the masks can be seen in Table 11 below.

Table 11. The following table contains the average Likert scores for the different criteria evaluated by the Mask Comfort Test. Each mask was assessed by three different people in random order.

COMFORT TEST SCORES	FIT TO FACE	BREATHABILITY	TEMPERATURE
Combined Fabric & Nylon Mask	3.33	3.33	3.67
Modified Gaiter	4.33	5.67	4.67
Wire Frame Mask	3.67	5.00	4.33

The weaknesses of the Mask Comfort Test should be noted. Due to the limited number of prototypes, the sample size of the test was small, at 3 participants. The fact that the participants were people close to the team members also introduces bias in the responses. These two factors may lead to reported Likert scores being higher than if a large, random selection of participants completed the test. The short period of the test as specified by the University of Iowa, being two minutes, may not guarantee an accurate long term comfort score for factors such as temperature and breathability. However, because the team wanted to follow the test conducted by the University of Iowa as closely as possible, this was not changed.

After selecting the final design, a follow-up Mask Comfort Test was conducted to verify the "is comfortable to wear" requirement. This follow-up test evaluates the final design's comfort with a slightly larger sample size. The score from this test, as presented in the Verification section, determines whether or not the mask reaches the specification for mask comfort set in the stakeholder requirements and engineering specifications.

Mask Filtration Efficiency Test

A Mask Filtration Efficiency Test was conducted in order to determine which combination of mask materials can filter out the greatest number of particles and to see how the number of uses and washes impacts the mask's filtration efficiency. This test enabled the team to confidently answer the design driver questions previously mentioned, made sure that the mask conforms to the filtration efficiency requirement, and allowed the team to choose what type of fabric to use for the final design. The Mask

Filtration Efficiency Test was conducted using a filtration efficiency testing apparatus in Professor Mirko Gamba's lab (Mirko, 2020). Figure 13 below shows a diagram of a similar testing apparatus used in a study conducted by the American Chemical Society, with the location of the fabric swatch, the particle sizers, and the particle generator labeled (Konda, 2020). Figure 14 shows the actual testing apparatus in Professor Gamba's lab.

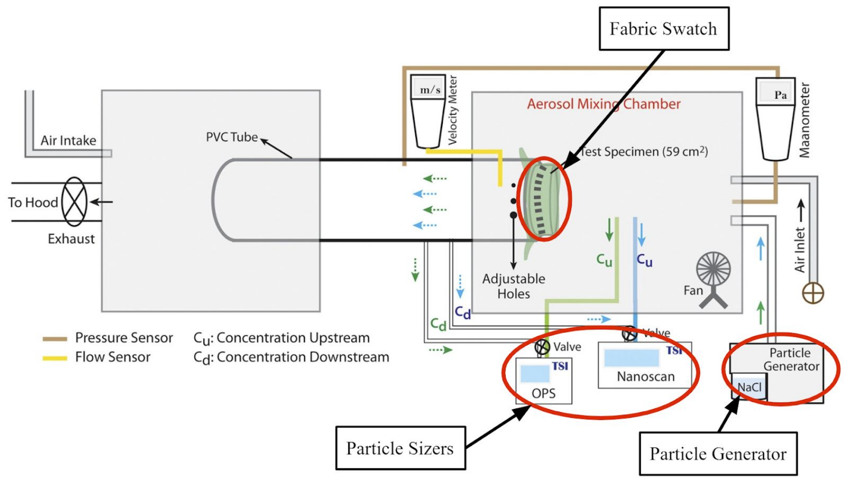


Figure 13. The above figure contains a diagram of a similar testing apparatus to the one in Gamba's lab. The location of the fabric swatch to be tested, particle sizers that measure the particle concentrations, and the particle generator that generates the aerosol sprayed through the fabric swatch are all labeled.

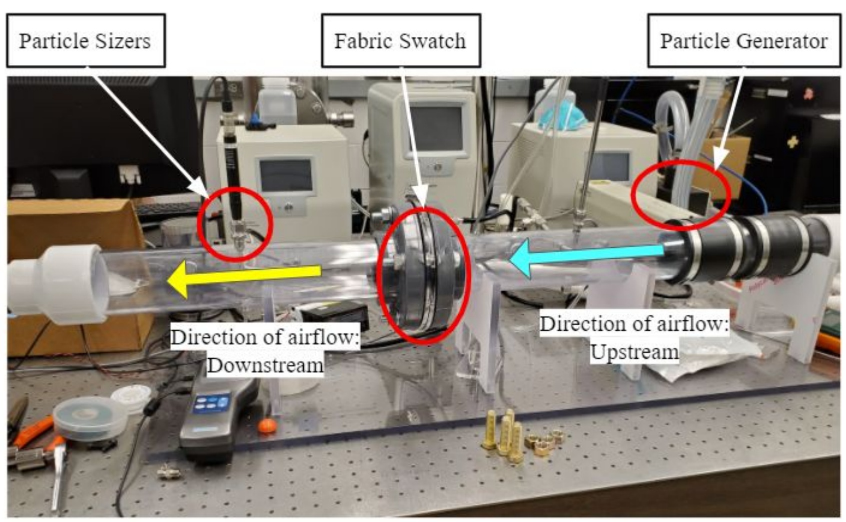


Figure 14. The above figure shows the testing apparatus in Professor Gamba's lab.

Access to this lab was acquired after meeting with Professor Gamba and discussing both the testing apparatus and the project. Conditions like temperature, humidity, particle speed, and particle size were inputted into the apparatus to match atmospheric conditions and the size and speed of a coronavirus particle as it travels through the air. It was decided that the temperature within the apparatus would be 21 degrees Celsius, the humidity would be 42%, the particle speed would be 0.10 m/s, and the particle size will be 0.1 micrometers (Climate, November 17, 2020; Average, November 17, 2020; Han, Z. Y., W. G. Weng, and Q. Y. Huang. 2013; N95s-Sufficient). While these parameters were chosen based on previous tests, the average cough speed of a human, and the average coronavirus particle size, in the future it is recommended that tests be done with other parameters to ensure that the mask filters particles efficiently at all ranges of temperatures, humidities, speeds, and particle sizes.

To conduct the test, a 5 inch by 5-inch fabric swatch was sealed in a holder inside of an enclosed tube. An aerosol salt solution matching the particle size and speed of coronavirus was then sprayed down the sealed tube and through the fabric swatch. Particle sizers measured the concentration of particles both upstream and downstream of the fabric swatch. The filtration efficiency was then calculated by comparing the number of particles that passed through the fabric to the amount that was filtered out by the fabric. Three combinations of fabrics were tested to determine which combination had the best filtration efficiency. These fabric combinations are shown in Figure 15 below.

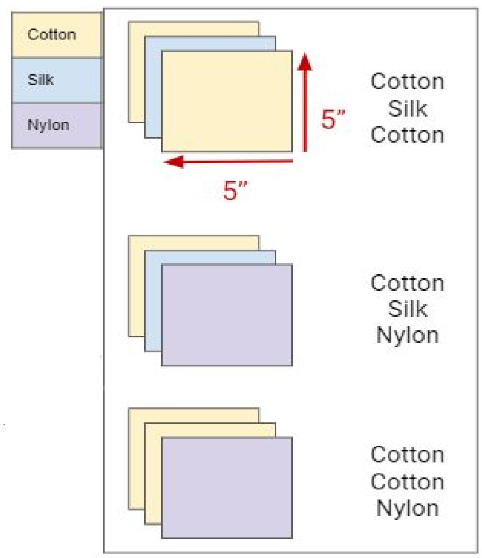


Figure 15. The above figure shows the three fabric combinations that were tested in Professor Gamba’s apparatus.

The three fabric combinations that were tested were selected based on previous filtration efficiency testing that had been conducted by the American Chemical Society on different double-layered material combinations (Konda, 2020). Since triple-layered fabric combinations had not been previously tested at the time of this test and nylon was not considered in their study despite it being a common material used in masks in Ghana and other nations, these three material combinations were deemed critical to test (KNUST, 2020). The fabric swatch with the best efficiency would be used in the final mask design.

The results that were gathered from the Mask Filtration Efficiency test were not able to be used accurately, as they were inconclusive. In order to conduct the test, Professor Gamba had to change many of the pre-set variables like particle size, humidity, and temperature. Due to the limited amount of time that was available to perform the testing, the test was more rushed than what was planned. There should've been a two hour period in which the testing apparatus was run without a sample for calibration. Instead, this window was shortened to thirty minutes. Furthermore, when the test was being performed, the particle counter stopped working, which hindered the ability to accurately measure the number of particles upstream and downstream. It is due to these errors that the test was deemed inconclusive and that the materials to be used were chosen based on literature.

Based on a study conducted by the American Chemical Society, the combination of silk and cotton has a filtration efficiency of approximately 95% for particles less than 300 nm in size (ACS, 2020). Furthermore, according to a study conducted by Virginia Tech, a mask with three layers with one layer being a tightly woven fabric up against the mouth gives a filtration efficiency of over 90% for a particle size of one micron (Virginia Tech Daily, 2020). This study was distributed to the public after this filtration efficiency test was conducted and confirms the team's design. It is based on these data results that the chosen fabric combination is cotton, silk, and nylon.

For future testing, it is recommended that more types of fabric be tested, as there could be materials other than nylon, cotton, and silk that are well suited for mask design and filtering COVID-19 particles. Additionally, the test should be conducted with fabric swatches that have been washed, which will simulate multiple uses and will show how the number of washes and uses changes the filtration efficiency of the mask. The degradation that could occur during 10 or 20 washes should be tested so a more accurate model of filtration efficiency degradation over subsequent uses can be constructed. These further recommended tests were unable to be completed by the team due to time constraints.

Mask Fabrication Test

As prototypes were being created, the time it took to make each prototype was recorded and notes were taken regarding the ease of creation and the materials used. This mode of analysis is appropriate because timing how long it takes to make each prototype provides a direct estimate of how long the prototype may take to create by the general population. Additionally, due to the fact that this test was meant to be conducted quickly and be used to compare different concepts, not much detail was required while still maintaining a high level of confidence in the test and the results. Each prototype was made one time by one team member without a detailed fabrication plan in place. The lack of a fabrication plan and a lack of sewing experience likely added time to each of the prototypes. Each prototype was sewn by hand using a needle and 100% polyester thread. Fabric was cut using utility shears due to the absence of sewing shears. This use of utility shears over sewing shears was acceptable, as people in low resource settings may not have access to sewing shears or the money to purchase sewing shears. The time it took to make each of the three prototypes is shown in Table 12 below.

Table 12. The following table contains the total amount of time it took to fabricate each prototype.

CONCEPT	FABRICATION TIME
Combined Fabric and Nylon Mask	2 hours
Modified Gaiter	1 hour 45 minutes
Wire Frame Mask	1 hour 30 minutes

The Combined Fabric and Nylon Mask took the longest amount of time to create. However, since it was the first mask to be constructed, it is likely that learning how to sew for the first time added to much of the fabrication time. Additionally, sewing by hand is naturally much slower than sewing with a sewing machine. In fabricating the mask, it was found to be very difficult to cut the nylon with utility shears, and the resulting cut fabric was very jagged. Determining the dimensions of the mask based on face size was also difficult to gauge, but this will be remedied as more work is put into a fabrication plan.

The Modified Gaiter was the second design to be prototyped and took slightly less time than the Combined Fabric and Nylon Mask. All of the cuts required for the gaiter were straight cuts. Additionally, the planned looseness of the fabric meant that a large piece of fabric could be cut without precise measurements. This intended looseness also remedies the issue of needing to make different sized masks for different face sizes and shapes, as the adjustable straps on the top and bottom edges of the gaiter allow for it to fit different face sizes. The primary drawback of the gaiter was the amount of material that was needed. The Modified Gaiter requires about 576 square inches of fabric to create, while the Combined Fabric and Nylon Mask only requires approximately 70 square inches of fabric.

The Wire Frame Mask was the third and final design to be prototyped and took the least amount of time to make. This shortened time is likely due to the learning curve that accompanies repeated sewing. The wire frame structure between the two pieces of cotton fabric was easy to mold but very difficult to sew between the fabric.

The results of this experiment indicate that each of the three concepts took a comparable amount of time to prototype. While it was originally specified that it should take no longer than 30 minutes to make the final concept, each prototype took more than triple that amount of time due to the fact that designs were prototyped by hand without a sewing machine. Additionally, in taking the required measurements for prototyping, the dimensions of the three designs were able to be determined. These dimensions are shown in Figures 7, 8, and 9 (pages 23-25) in the Prototyping subsection. The prototypes were created to fit the mannequin head so that the Mask Fit Test could be conducted on them. Ultimately, this test indicated that the Modified Gaiter and Wire Frame Mask should not be considered for the final solution, as the Modified Gaiter required much more material to create than the other designs and the Wire Frame Mask was very hard to fabricate. In the future, this analysis should be completed by multiple team members to gather more data points on fabrication time. Additionally, the order in which the masks are prototyped should be changed to combat the learning curve.

Risk Assessment

To complete a general risk assessment of the team's final mask design, a Failure Modes and Risks Analysis (FMEA) was conducted by a member of the team. This can be seen below in Table 14 (page 36). Severity rankings were based on definitions found in Table 13 (page 35). Occurrence and detection rankings were chosen based on how obvious a failure would be when someone wears a mask actively. No high-level risks were identified, due to the project being hand-made rather than machined or built with power tools. The results of the FMEA show that flaws in the physical design were the main concerns. For the design, three areas of interest are the front-piece (or the area of the mask covering the mouth and nose), the ear hole, and the wiring within the mask. Failures in these components would cause the mask to become temporarily unusable. If the front-piece were to fail, the mask may be permanently unusable. Extra attention was paid to these components when creating the design to ensure user safety as they create their masks. The risk of ineffective COVID-19 filtering was identified as another risk, and due to the nature of the virus, was assigned the highest possible severity ranking. This factored into the amount of testing the team conducted and planned during the last half of the semester. Additional testing concerning this topic could be completed in the future to increase the confidence in the results achieved. For the near future, however, current restrictions on building access due to COVID-19 and the semester ending will make it unlikely for the team to collaborate with Professor Gamba on additional testing.

Table 13. The following table contains rankings for estimated severity of failures in FMEA (FMEA, 2020). These rankings and their definitions were used to determine the component rankings in the FMEA.

Severity Rankings			
Ranking	**Effect**	**Design FMEA Severity**	**Process FMEA Severity**
10	Hazardous-no warning	affects safe operation without warning	may endanger machine or operator without warning
9	Hazardous- w/ warning	affects safe operation with warning	may endanger machine or operator with warning
8	Very High	makes product inoperable	major disruption in operations (100% scrap)
7	High	makes product operable at reduced performance (customer dissatisfaction)	minor disruption in operations (may require sorting and some scrap)
6	Moderate	results in customer discomfort	minor disruption in operations (no sorting but some scrap)
5	Low	results in comfort and convenience at a reduced level	minor disruption in operations (portion may require rework)
4	Very Low	results in dissatisfication by most customers.	minor disruption in operations (some sorting and portion may require rework)
3	Minor	results in dissatisfication by average customer.	minor disruption (some rework but little affect on production rate)
2	Very Minor	results in dissatisfication by few customers.	minor disruption (minimal affect on production rate)
1	None	No effect	No effect

Table 14. The following table contains the FMEA conducted for the project. The risk preference number was calculated by multiplying the severity, probability of occurrence, and probability of detection. The higher the number, the higher the risk associated with the corresponding failure mode.

FAILURE MODE	SEVERITY	PROBABILITY OF OCCURRENCE	PROBABILITY OF DETECTION	RISK PREFERENCE NUMBER
Mask front-piece fails	8	2	10	160
Mask ear hole fails	7	2	10	140
Mask fails to filter COVID-19	10	3	3	90
Mask is not washed routinely	4	7	1	21
Mask is used past lifetime	4	6	1	24
Mask wire fails or causes pain	5	2	10	100
Mask is uncomfortable	1	2	10	20

Design Solution

The design solution is a DIY mask made of cotton, silk, nylon, and aluminum wire, the latter of which can be substituted with pipe cleaners. The design is meant to be hand-sewn, as access to sewing machines in low resource settings is not guaranteed. The filtration layer of the mask is double-layered, with the inner layer (the layer touching the face) being cotton and the outer layer being silk. These fabrics were chosen due to their high filtration efficiency as found in literature (Konda, 2020). There is then a layer of nylon on the outside covering both the filtration material and wrapping around the ears. Since nylon is a better forming material, this external layer allows the mask to fit better to the face and provides a better seal around the edges. The ear connection is made of the same nylon fabric, as nylon was found to be more comfortable than traditional elastic loops. The cotton and silk filtration fabric combination has pleats along the side edges to allow for more space between the mouth and the mask and to allow for the mask to stretch and compress while the mouth is moving. This feature was added upon analyzing the results of the Comfort Priority Survey, in which the mask sliding down the face while talking was noted as a common complaint. An aluminum wire (or pipe cleaner) is located both over the nose and under the chin. The wire over the nose was in the initial design. The wire under the chin was added after conducting the Mask Fit Test during the engineering analysis. The Wire Frame Mask, which had a wire located under the chin, had reduced air flow around the bottom edge of the mask. Therefore, the wire was added as a component of the final design solution to allow for a better fit. The final DIY mask design is shown in Figure 16 (page 37) below. The final design created by the team is shown in Figure 17 (page 37) below. It is important to note that dimensions were purposefully not included in the design drawing, as the dimensions change depending on the dimensions of the user's face. This dimensional component is accounted for in the instructions to create the mask.

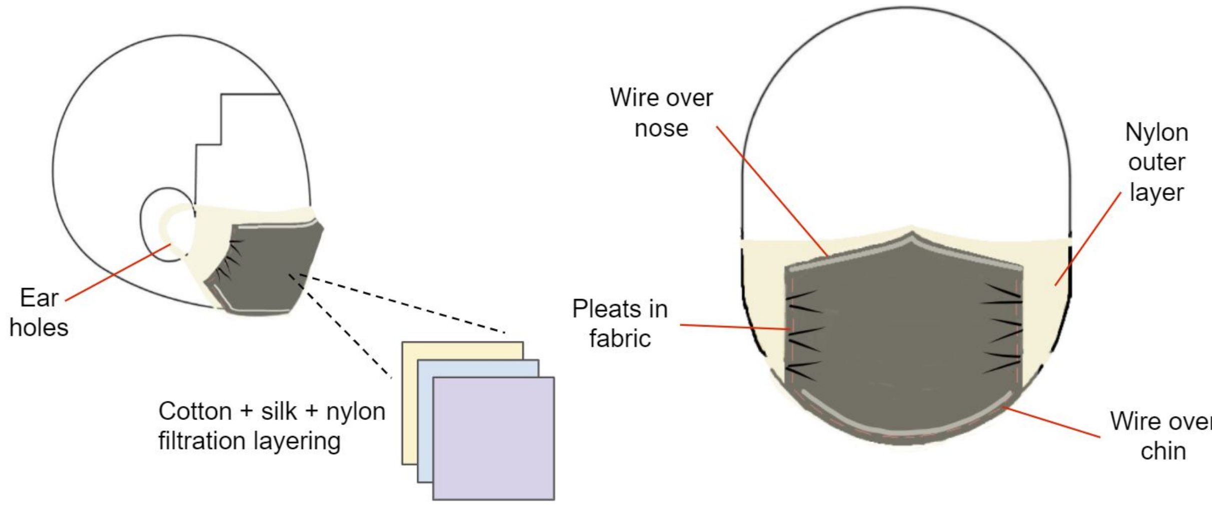


Figure 16. The above image displays the design solution. Key components of the mask are labeled in addition to the filtration layering.

Figure 17. The above images display the physical design solution. The left image shows the mask attached to a mannequin head to simulate use. The right image shows the side of the mask that rests against the face, with a red and black checkered cotton layer and the outer grey nylon layer. There is a layer of silk between the cotton and nylon layers.

Based on the results of the engineering analysis, there is great confidence that this final design addresses all stakeholder requirements and meets all corresponding specifications. The materials used in the mask are both low cost and available in low resource settings as confirmed by local area experts in Ghana (KNUST Team, 2020; Ama, 2020; Afia, 2020). With the wire under the chin added as a result of the Mask Fit Test, the mask effectively minimizes air flow around the edges when compared to other designs. With the pleats added as a result of the Mask Comfort Test and Comfort Priority Survey, the mask is comfortable to wear. Upon completing the Mask Fabrication Test, it was determined that the design solution is also easy to create and does not use too many materials, as the Modified Gaiter did. Lastly, while further filtration efficiency testing is recommended to obtain more accurate results, the selected filtration fabrics of cotton and silk provide for the best filtration efficiency as specified in literature (Konda, 2020). The actual performance of the final design and the verification of requirements is located in the Verification section.

The detailed manufacturing plan to create the mask with corresponding pictures is located in Table A.3 in Appendix A (page 61). The manufacturing plan doubles as the DIY instructions for creating the mask. Additionally, the materials used to create the mask as well as their cost in the United States is located in Table A.2 in Appendix A (page 58). Overall, the mask costs approximately $1.43 USD, with all of the costs coming from the materials. Since the mask is meant to be created by the end-user, labor costs are negligible.

The main use phases of the mask involve construction, use, wash, and disposal. As previously mentioned, the construction phase is addressed by the set of instructions provided for creating the mask. The use phase is similar to the mask-wearing recommendations made by the CDC (Centers for Disease Control and Prevention, 2020b). The mask should be worn in any public setting. One use constitutes any period of time from which the mask is worn to when the mask is taken off when the user comes within 6 feet of another person. The mask should be washed after each use to effectively decontaminate any particles that remain on it. The mask can be incorporated into a traditional clothes washing cycle practiced in any household. In Ghana specifically, where washing machines are less common, it is recommended to soak and scrub the mask by hand in tepid water with laundry detergent (KNUST, 2020). As found in literature, the mask has an approximate lifetime of 20 uses and should be disposed of by the user after (Oh, 2020; Centers for Disease Control and Prevention, 2020f). Since the mask may come in direct, repeated contact with COVID-19 particles throughout its use, it should be disposed of after and no part of the mask should be reused after the lifetime has been met. The mask can be disposed of in the trash to be later sent to a landfill.

Verification

To verify the final design solution and determine whether or not it meets the stakeholder requirements and engineering specifications, several different verification methods were used.

To verify the "is low cost" requirement, the cost of the cotton and silk necessary in the mask designs was determined in Ghana through contact with Afia, a community member who works with textiles. She indicated that the price of 1 square meter of cotton is, on average, $6.52 USD. Likewise, the price of 1 square meter of silk is, on average, $2.74 USD (Afia, 2020). These prices were then scaled down to determine the cost for the specific dimensions in the final design of $0.12 USD and $0.05 USD for cotton and silk respectively. These prices were then averaged together and divided by their average costs in the United States to determine a cost factor that represents the ratio between prices in Ghana and prices in the United States. This cost factor, determined to be 0.239, was then used to calculate the prices of the other mask components in Ghana. Upon calculating component costs and summing them together, the total price of the design solution in Ghana was found to be around $0.34 USD, which translates to 2 cedis. This is directly equal to the engineering specification, proving this requirement to be fulfilled (Ama, 2020). which fulfills the specifications.

To verify the “minimizes air flow around edge of mask” requirement and determine the fit factor of the final solution concept, specialized equipment is required that is both expensive and difficult to use within the constraints imposed by the COVID-19 pandemic. While this requirement was not verified by the end of the course, a procedure is outlined as to how the fit could be determined for the chosen concept based on a past study done by the Society of Disaster Medicine and Public Health (Davies, 2013). A Model 8095 N95-Companion Mask Fit Tester and TSI PortaCount Plus Respirator Fit Tester was used to assess the fit of different homemade masks. The fit tester contains instructions as to how to set up the particle generator, fit tester, and testing probe (Model, 2010). It then outlines steps to complete the test and collect data using an accompanying PortaCount Plus Respirator Fit Tester Operation Manual (PORTACOUNT, 2015). To test the DIY masks, the fit tester would be placed around a volunteers neck. Then, the volunteer would don their DIY mask with no help or guidance and take two minutes to ensure that the mask is comfortable. A measurement probe would be located between the mask and the face. Once particles that may be trapped inside the mask are purged, the fit test in the manual would be conducted while volunteers perform seven consecutive exercises, each lasting 96 seconds. The seven exercises include normal breathing, deep breathing, head moving side to side, head moving up and down, talking aloud using a prepared paragraph, bending at the waist as if touching their toes, and normal breathing (Davies, 2013). During each of these exercises, the probe would measure the concentration of particles inside the mask while a particle sizer on the fit tester measures the concentration of particles outside of the mask. The ratio of the interior particle concentration to the exterior particle concentration constitutes the fit factor, which can be directly compared to the engineering specification. If this test were able to be performed and if the COVID-19 pandemic weren’t a limiting factor, multiple volunteers would be asked to complete the fit test with the entire team supervising to get multiple sets of data. If the calculated fit factor is greater than or equal to 2, then the requirement would be verified.

To verify the “has good filtration efficiency” requirement, results from the Mask Filtration Efficiency Test as conducted in the engineering analysis and described in the Engineering Analysis section were considered. While issues arose during testing that restricted the collection of valid data, a plan for verification should be noted. With the three different fabric swatch samples tested in Professor Gamba’s lab, the best fabric swatch would be chosen as the filtering material for the final solution concept. Since the filtration efficiency would be obtained for the different material options, the data could be directly compared with the engineering specification of a 50% filtration efficiency to determine whether or not the solution meets the specification. Although more testing is required to collect accurate data, literature shows that the combination of silk and cotton has a filtration efficiency of approximately 95% for particles less than 300 nm in size (ACS, 2020). Since the design solution uses cotton and silk in addition to the outer nylon layer, it can be assumed that the proposed solution has a filtration efficiency higher than 95%. Since this 95% efficiency is higher than the specification of 50% efficiency, this requirement is verified through literature. However, it is still recommended that further testing occur to obtain data regarding the effect of the additional nylon layer.

The verification of the "uses available resources" requirement was done implicitly. Throughout the course of the project, only materials that were confirmed to be available in Ghana were considered. Contacts in Ghana have confirmed that all of the materials including silk, which was assumed to be more expensive and less available, are inexpensive and available.

To verify the "is comfortable to wear" requirement, the Mask Comfort Test as outlined in the Engineering Analysis section was conducted using the final modified solution concept. Housemates and family members were asked to wear the prototype and assess it based on the three metrics of comfortable fit to face, temperature, and breathability using a six-point Likert scale. The results of this second run of the Mask Comfort Test are shown in Table 15 below.

Table 15. The following data contains the Likert scores for the design solution for the three metrics of comfort: fit to face, breathability, and temperature.

COMFORT TEST SCORES	FIT TO FACE	BREATHABILITY	TEMPERATURE
Design Solution	4.33	4.67	4.33

Since the Likert scores for the comfort metrics are all above 4 as specified, the design solution meets the comfort requirement. However, it should be noted that, since this test was only conducted on 5 participants in a limited setting, further testing should be conducted in low resource settings to more accurately verify this requirement.

To verify the "has a long lifetime" requirement, a plan was made to use the apparatus and results from the Mask Filtration Efficiency test. The original intent was to test fabric swatches after both 0 washes and 20 washes and to note the potential drop in filtration efficiency. If the filtration efficiency after 20 washes stayed above 50%, then the solution would have satisfied the specification. However, due to the limited time allowed in the testing lab and the need to test a different team's samples, these tests were unable to be conducted. It stands that the "has a long lifetime" requirement is currently unverified.

To verify the "is easy to create by general population" requirement, a use test was conducted to determine how long it takes to create the solution. A single family member was given instructions on how to create the concept. It took approximately 30 minutes to create the mask by hand, with the instructions consisting of 10 steps. Since the specification stated the mask should be able to be created in less than or equal to 30 minutes with less than 12 steps, this requirement was verified.

DISCUSSION AND RECOMMENDATIONS

Upon completing the project, several changes have been identified that may have improved the process or further improved the results. The first major change is in regards to stakeholder communication and securement of testing equipment. Due to time constraints, filtration efficiency testing was unable to be completed and the fit testing was unable to be performed. Each of these tests required the use of Professor Mirko Gamba's lab. While Professor Gamba was contacted early in the semester, even earlier and more organized coordination could have allowed for more testing time, which would have led to the successful verification of the filtration efficiency, fit, and lifetime requirements. Since filtration efficiency and fit are two of the most important requirements, being unable to verify them in the lab is the greatest weakness of this project. Additionally, being unable to verify the lifetime of the mask means that the recommendation provided for the number of potential uses is an estimate.

Another weakness of the design is that a basic knowledge of sewing is needed to construct the mask. Although not much skill is required to create the final design solution, it does make the mask inherently more difficult to create than a mask that is unsewn. However, the final solution does have many strengths. As stated before, the low skill floor needed to sew the mask makes the design fairly easy to create. After giving a family member a 10-step instruction set on how to create the mask, it took them less than 30 minutes to sew the mask together. The materials used are easy to obtain in low resource settings and have low costs. Contacts in Ghana have confirmed the materials' availability and cheap price point, costing only 0.34 USD or 2 cedis to make one mask (Afia, 2020). The mask has also been proven to be comfortable, scoring an average of 4.4 out of 6 on the Likert scale, with 6 being most comfortable and 1 being least comfortable. This score was determined by averaging the comfort score for each of the following metrics: fit to face, temperature, and breathability.

In the future, the team recommends that further filtration efficiency testing be conducted to verify both the filtration efficiency and lifetime requirements. It is also recommended that the filtration efficiency apparatus in Professor Gamba's lab be retrofitted to conduct a makeshift fit test. By placing the mask on a mannequin head in a control volume (box), the particle sizers and particle generator in the filtration efficiency testing apparatus can be used to measure the concentration of particles both inside and outside of the mask. Additionally, it is recommended that the Mask Comfort Test be conducted with a larger population. Since the COVID-19 pandemic limits the distribution of mask prototypes, only a very small number of people in the US were able to rate the mask based on comfort. Since the target population of the project is people who live in low resource settings, safely distributing masks to them to gather feedback on comfort is recommended to take into account differences in the interpretation of comfort around the world. Lastly, a way to lift the mask off of the face to provide greater comfort is recommended.

CONCLUSION

The purpose of this design project was to develop a DIY mask to combat the shortage of N95 respirators and medical masks in low resource settings. Meetings with stakeholders were conducted, which provided valuable insight into potential areas of focus and potential access to a testing apparatus to test the filtration efficiency of different materials. Research was conducted on the areas of focus suggested by the stakeholders to develop requirements and specifications. The mask should be low cost, costing less than 2 cedis, or $0.34 USD (Ama, 2020). The mask should minimize the air flow around the edge, having a fit factor greater than or equal to 2. The mask should be made in less than 30 minutes with fewer than 12 steps of instructions (Centers for Disease Control and Prevention, 2020e; Bound Tree, 2020; Gierthmuehlen, 2020; Khong, 2020). The mask should filter over 50% of particles over 50 nm in size (Davies, 2013; Advances, 2006). The mask should also be comfortable to wear with average scores greater than 4 on a 6 point Likert scale (Purdy, 2019). Finally, the mask should sustain a long lifespan, supporting over 20 uses with a decontamination cycle in between each use (Oh, 2020; Centers for Disease Control and Prevention, 2020f).

Design heuristics were used for initial concept generation during a brainstorming session. This produced over 60 concepts which were then organized into a morphological matrix. From this point, 11 concept designs were made and evaluated using a decision matrix, producing a ranking for the designs. The design with the highest aggregate score as well as the two runner-up designs were selected to be prototyped. A testing plan was developed and executed to test the masks. The tests conducted included measuring mask construction time, comparing mask fit by measuring air flow, evaluating the comfort of the masks, and a filtration efficiency test, the latter of which proving inconclusive due to time constraints and technical issues. From the completed tests, a final design solution was made that utilizes the strongest aspects of different initial concepts. These engineering analyses were also used to verify the "is comfortable to wear" requirement. The "is low cost" and "uses available resources" requirements were verified through research and calculations. The "is easy to create" requirement was verified through a user test. Unfortunately, because the filtration efficiency test did not go as intended, the "has good filtration efficiency" and "has a long lifetime" requirements could not be verified. The "fits to face" requirement is also unverified due to time and cost constraints.

By the end of the project, a design and instructions on creating the design were created. This design has been verified to fulfill 4 out of 7 requirements, with the filtration efficiency, lifetime, and fit to face requirements unverified due to COVID restrictions and insufficient testing ability. If the project were to be continued, effort would be made on verifying these unverified requirements.

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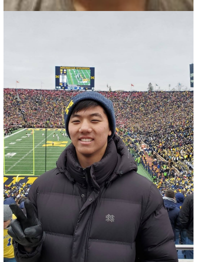

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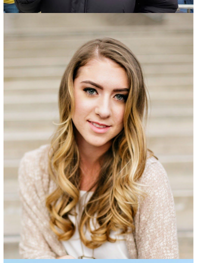

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APPENDIX A: Tables, Figures, and Manufacturing Plan

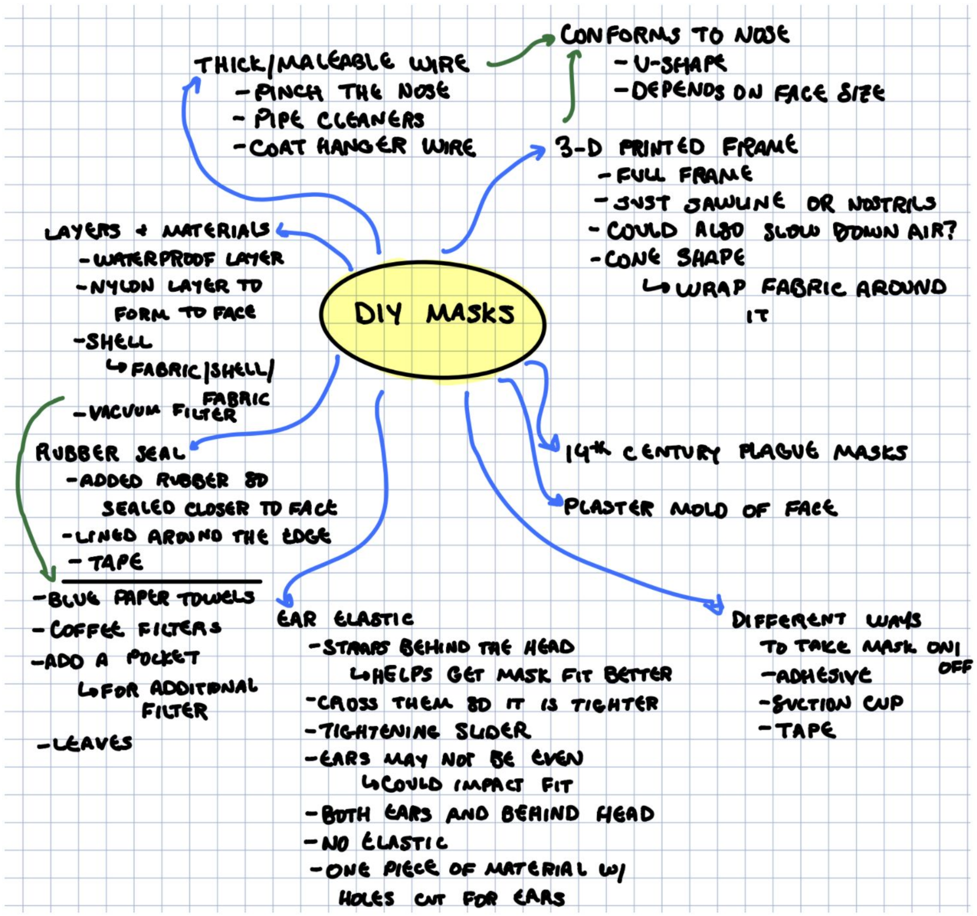


Figure A.1. The above mind map contains initial concept generation and ideation.

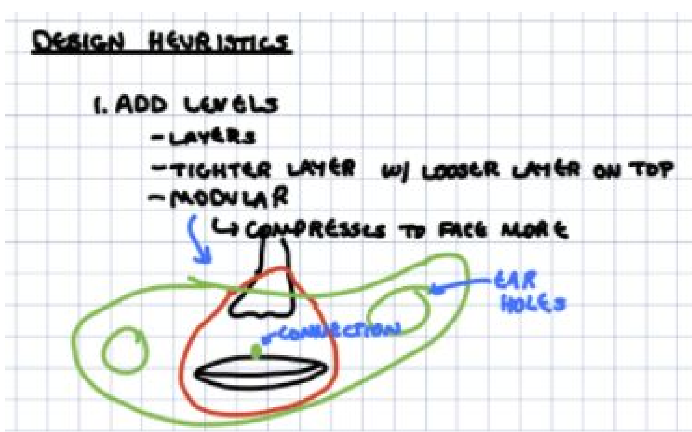


Figure A.2. The above figure contains notes taken at the beginning of the brainstorming process using design heuristics.

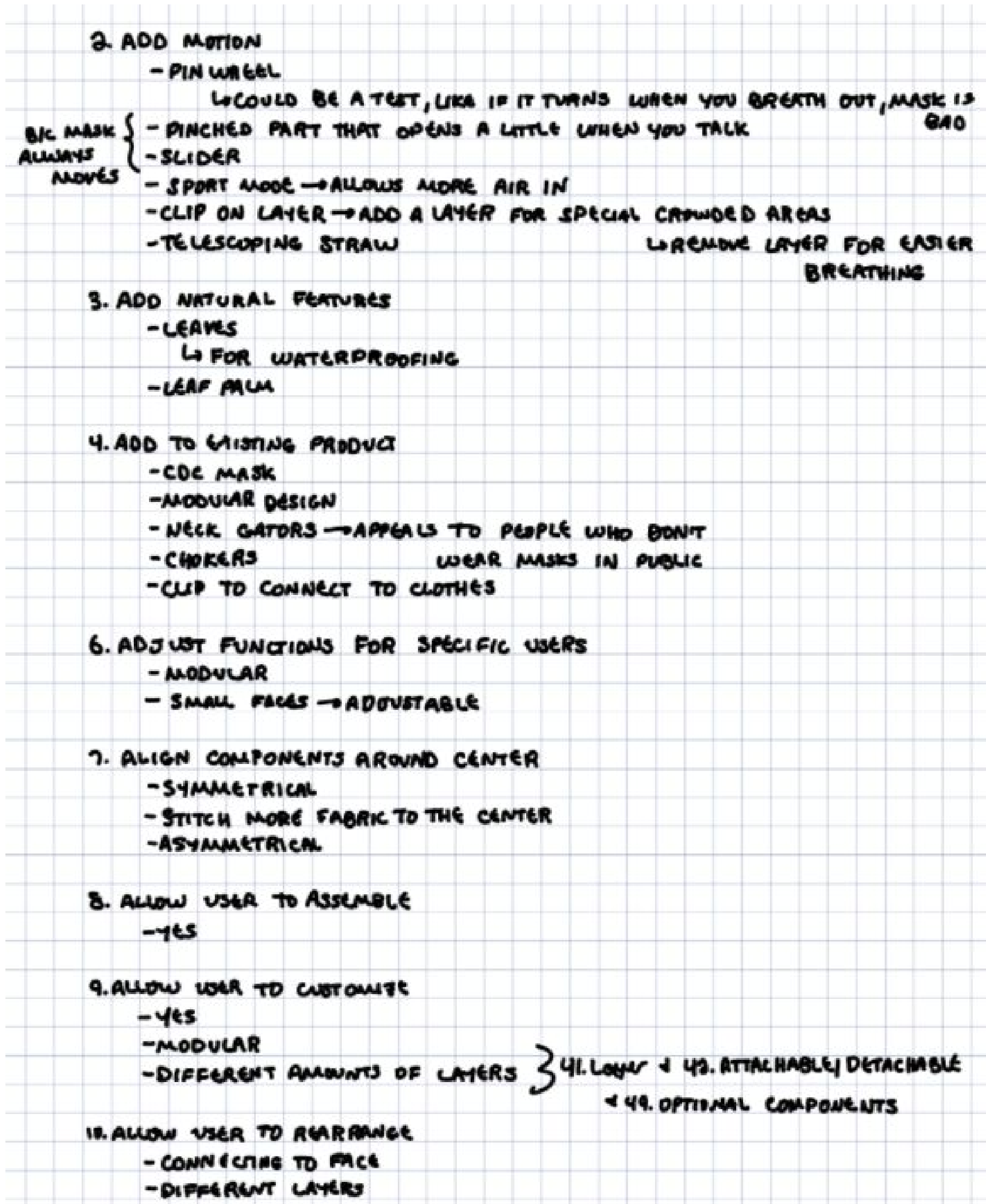
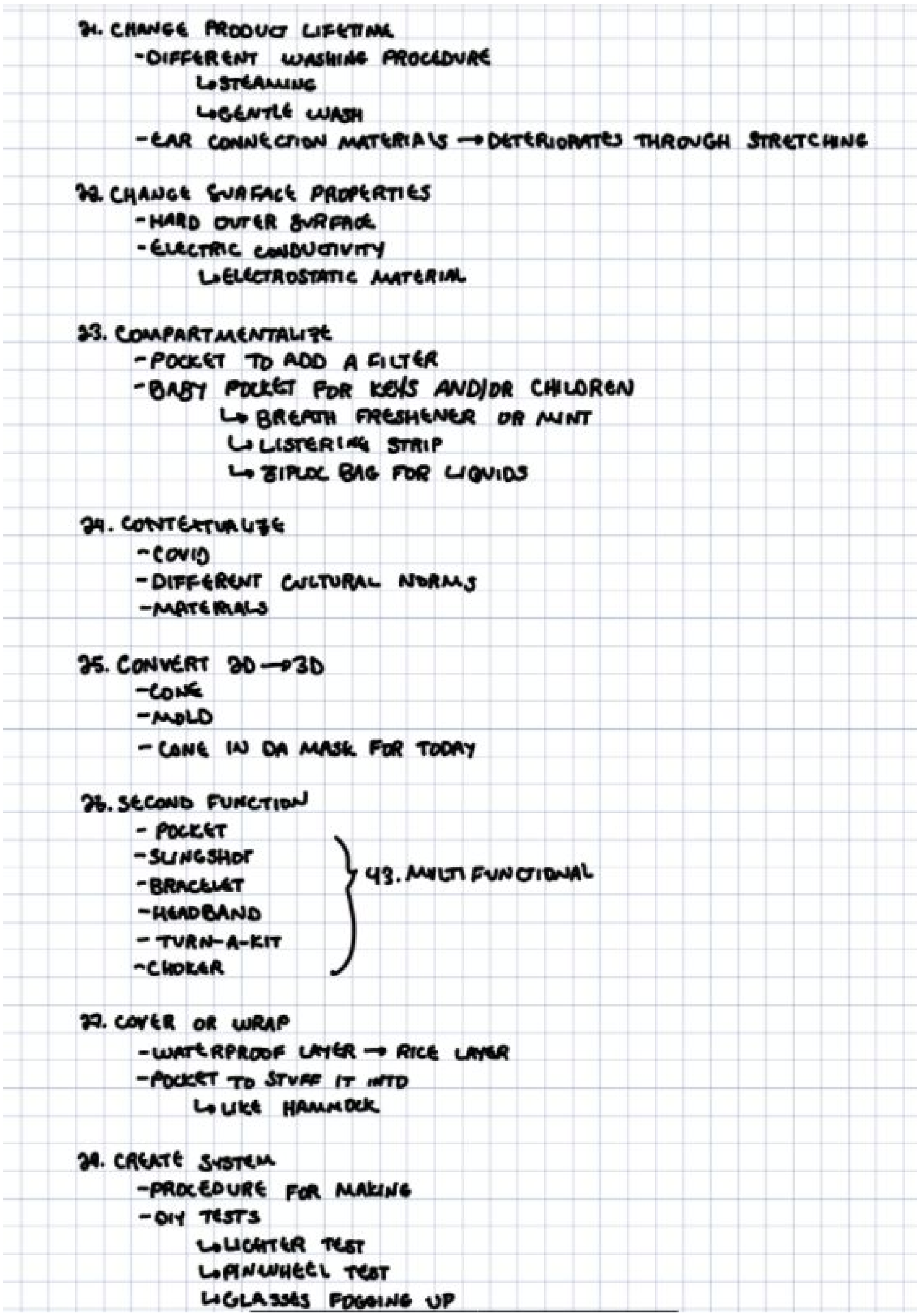

2. ADD MOTION
- PIN WHEEL
↳ COULD BE A TEST, LIKE IF IT TURNS WHEN YOU BREATH OUT, MASK IS BAD
BIG MASK ALWAYS MOVES { - PINCHED PART THAT OPENS A LITTLE WHEN YOU TALK
- SLIDER
- SPORT MODE → ALLOWS MORE AIR IN
- CLIP ON LAYER → ADD A LAYER FOR SPECIAL CROWDED AREAS
- TELESCOPING STRAW ↳ REMOVE LAYER FOR EASIER BREATHING
3. ADD NATURAL FEATURES
- LEAVES
↳ FOR WATERPROOFING
- LEAF PALM
4. ADD TO EXISTING PRODUCT
- CDC MASK
- MODULAR DESIGN
- NECK GATORS → APPEALS TO PEOPLE WHO DON'T
- CHOKERS WEAR MASKS IN PUBLIC
- CLIP TO CONNECT TO CLOTHES
6. ADJUST FUNCTIONS FOR SPECIFIC USERS
- MODULAR
- SMALL FACES → ADJUSTABLE
7. ALIGN COMPONENTS AROUND CENTER
- SYMMETRICAL
- STITCH MORE FABRIC TO THE CENTER
- ASYMMETRICAL
8. ALLOW USER TO ASSEMBLE
- YES
9. ALLOW USER TO CUSTOMIZE
- YES
- MODULAR
- DIFFERENT AMOUNTS OF LAYERS } 41. LAYER + 42. ATTACHABLE/DETACHABLE + 44. OPTIONAL COMPONENTS
10. ALLOW USER TO REARRANGE
- CONNECTING TO FACE
- DIFFERENT LAYERS

Figure A.3. The above figure contains notes taken during the brainstorming process using design heuristics.


17. BUILD USER COMMUNITY
- HAVE A WAY TO PROVE COMFORT
19. CHANGE FLEXIBILITY
- PLASTIC FRAME
↳ SODA BOTTLE

Figure A.4. The above figure contains notes taken during the brainstorming process using design heuristics.


21. CHANGE PRODUCT LIFETIME
-DIFFERENT WASHING PROCEDURE
↳STEAMING
↳GENTLE WASH
-EAR CONNECTION MATERIALS → DETERIORATES THROUGH STRETCHING

22. CHANGE SURFACE PROPERTIES
-HARD OUTER SURFACE
-ELECTRIC CONDUCTIVITY
↳ELECTROSTATIC MATERIAL

23. COMPARTMENTALIZE
-POCKET TO ADD A FILTER
-BABY POCKET FOR KEYS AND/OR CHILDREN
↳BREATH FRESHENER OR MINT
↳LISTERING STRIP
↳ZIPLOC BAG FOR LIQUIDS

24. CONTEXTUALIZE
-COVID
-DIFFERENT CULTURAL NORMS
-MATERIALS

25. CONVERT 2D → 3D
-CONE
-MOLD
-CONE IN DA MASK FOR TODAY

26. SECOND FUNCTION
- POCKET
-SLINGSHOT
-BRACELET
-HEADBAND
- TURN-A-KIT
-CHOKER
} 43. MULTI FUNCTIONAL

27. COVER OR WRAP
-WATERPROOF LAYER → RICE LAYER
-POCKET TO STUFF IT INTO
↳LIKE HAMMOCK

28. CREATE SYSTEM
-PROCEDURE FOR MAKING
-DIY TESTS
↳LIGHTER TEST
↳PINWHEEL TEST
↳GLASSES FOGGING UP

Figure A.5. The above figure contains notes taken during the brainstorming process using design heuristics.

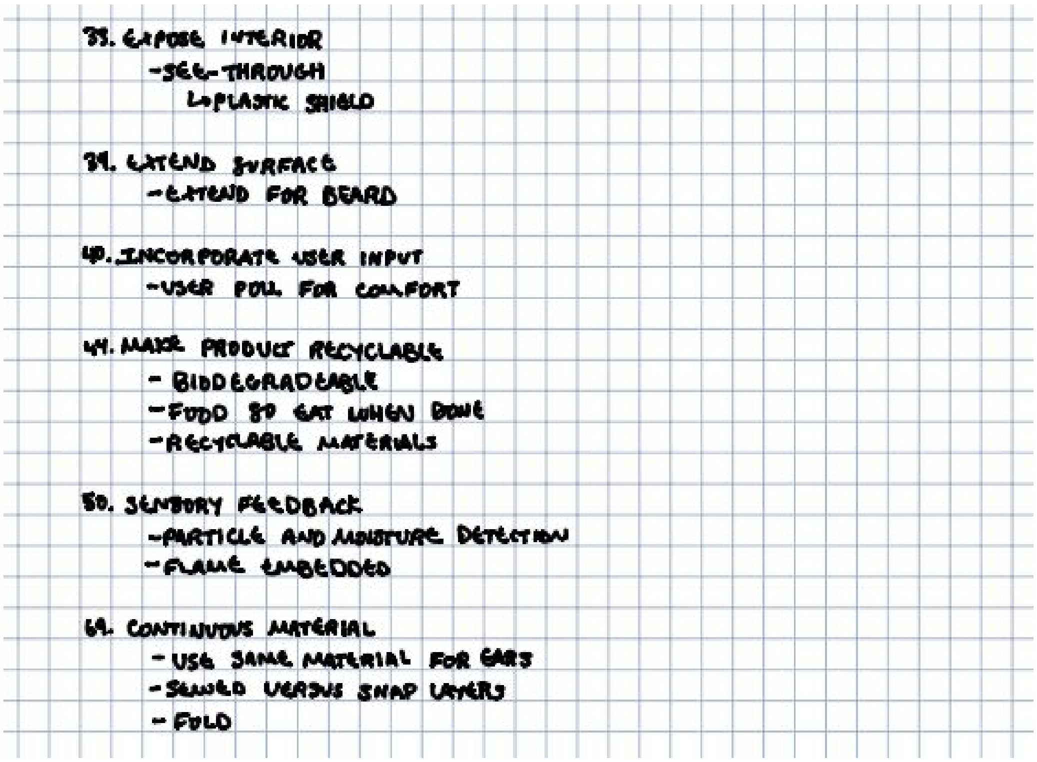


Figure A.6. The above figure contains notes taken during the brainstorming process using design heuristics.

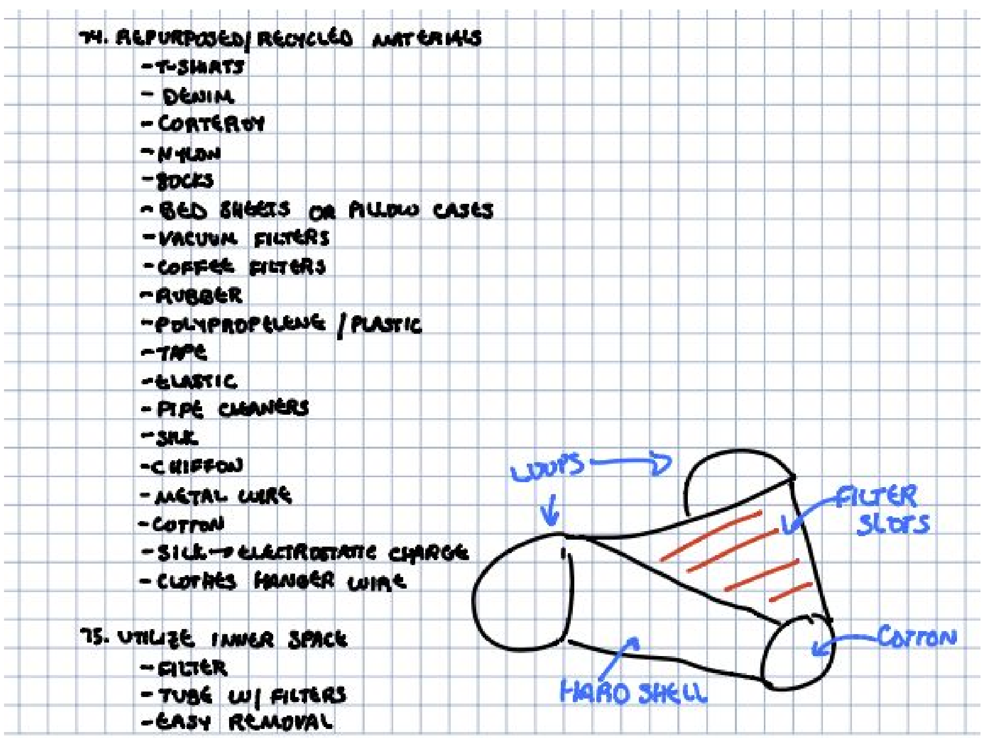
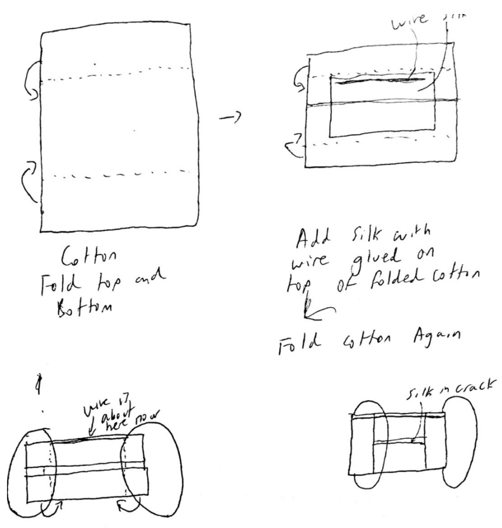


Figure A.7. The above figure contains notes taken during the brainstorming process using design heuristics.

Categories	Potential Component Ideas						
	Elastic	Rubber bands	Hair ties	Straps behind head	Tightening slider	Both ears and behind head	Suction Cup
Face connector	Material straps	Crossed straps	Adhesives				
	1	2	3	4	5	Clip on layer	Folded layers
Layers	Sport mode	Tighter layer w/ looser layer on top	More fabric in the center				
	Waterproof layer	Nylon	Vacuum filters	T-shirt cotton	Tightly woven cotton	Silk	Tape
	Shop towel	Denim	Coffee filters	Bed sheets	Leaves	Plastic shield	Pillow Cases
Materials	Polypropelene/Plastic	Leaves	Metal Wire	Rice	Chiffon	Corduroy	Socks
	Pipe cleaner for nose	Rubber seal	Thick maleable wire	Coat hanger wire	Soda bottle	Neck gaiter	String
	3D Printed Frame	Cone Shape	Symmetrical	Asymmetrical	Hard outer surface	Tubes with filters	Facial mold
Structure	Extended surface for facial hair	Insertable Filters	17th century plague mask				
Customizable	Modular	Different amount of layers	Different type of layers	Different ways to attach to face			
User Side	Created by user	Procedure for making mask	DIY tests for fit and filtration	User poll for comfort			
Context	Covid	Different cultural norms	Available Materials				
Held together by	Sewn	Folded/friction	Glue	Snaps	Tape	Electric conductivity (static)	Magnetic
	Pocket for filter	Pocket to stuff mask into	Choker	Pinwheel for testing	Pinched part that moves as you talk	Slider	Telescoping Straw
	Clip to connect to clothes	Slingshot	Gaiter	Edible	Adjustable	Breath freshener	Bracelet
Extras	Headband	Tourniquet	Flame embedded	Pocket to stuff mask into	Clear shield	Recyclable	Biodegradable

Figure A.8. The above figure contains the morphological chart used during concept development.

Modified Folded Mask



Snap Layer Mask

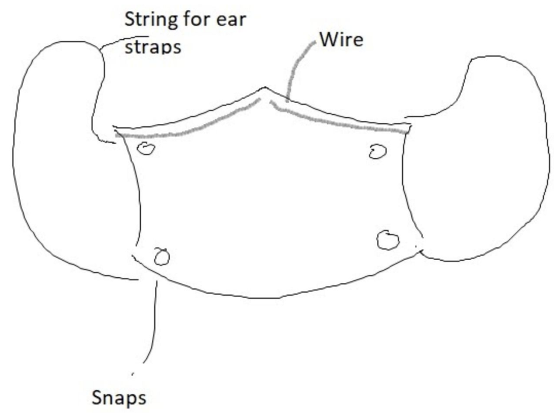


Figure A.9. The above figure contains the two remaining mask concepts not discussed in the report.

Table A.1. The following table contains the bill of materials which includes each item bought for the entirety of the prototyping phase, the amount of material purchased, and the cost for budgeting purposes.

MATERIAL	AMOUNT	COST
Cotton (100% Cotton)	2 yards x 1 yard	$14.98
Nylon (82% Nylon, 18% Spandex)	2 yards x 1 yard	$20.38
Silk (100% Silk)	1 yard x 1 yard	$25.99
Aluminum Wire (12 Gauge Wire, 100% Aluminum)	2 spools (3 yards of wire/spool)	$6.98
Thread (100% Polyester)	3 spools (274 yards of thread/spool)	$13.47
Total		**$81.80**

Table A.2. The following table contains the bill of materials for the updated Combined Fabric and Nylon Mask. This does not include the tools required for construction (needle and scissors).

MATERIAL	AMOUNT	COST
Cotton (100% Cotton)	5 inches x 5.5 inches	$0.16
Nylon (82% Nylon, 18% Spandex)	5 inches x 10 inches	$0.39
Silk (100% Silk)	5 inches x 5.5 inches	$0.55
Aluminum Wire (12 Gauge Wire, 100% Aluminum)	5 inches * 2 wires	$0.32
Thread (100% Polyester)	48 inches	$0.01
Total		**$1.43**

Comfort Priority Survey

Q0 This survey is part of an engineering student design project at the University of Michigan. The purpose of this survey is to gather information regarding what people prioritize when it comes to protective face masks. This survey is anonymous, and does not ask for or collect any sensitive information. Your participation in this survey is voluntary, and you can withdraw from participating at any time. The results of this survey will strictly be used for scholarly purposes and will not be published. Estimated completion time is 5 minutes.

Q1 What type of masks do you primarily use? (select all that apply)

- ▢ Fabric mask (i.e. commercially produced fabric mask, purchased from a store)
- ▢ DIY mask (i.e. mask that either you made or someone else made for you)
- ▢ Surgical mask
- ▢ N95 respirator
- ▢ Neck gaiter
- ▢ I do not wear a mask
- ▢ Other

Q2 If you answered "Other" to the previous question, please describe the mask that you use.

____

____

____

____

____

Q3 On average, how many hours per day do you typically wear your mask?

o <1 hour

o 1-2 hours

o 3-4 hours

o 5-6 hours

o >6 hours

Q4 In regards to **face masks**, how much **do you agree** with each of the following statements?

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
It is important to me that my mask is breathable	o	o	o	o	o
It is important to me that my mask is neither too tight nor too loose	o	o	o	o	o
It is important to me that my mask does not irritate my skin	o	o	o	o	o

It is important to me that my mask does not cause sweat build-up on my face	o	o	o	o	o
It is important to me that my mask protects me or those around me from COVID-19	o	o	o	o	o

Q5 Of the masks you have worn, which do you like the least? Please describe what about that mask makes it your least favorite.

____

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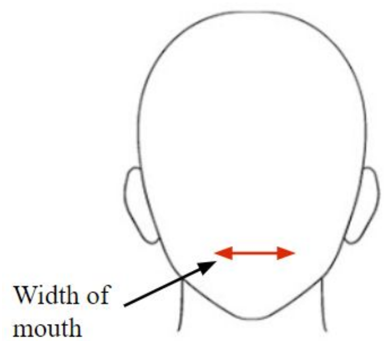
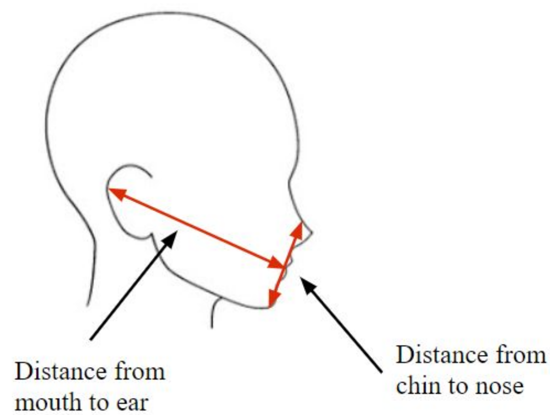
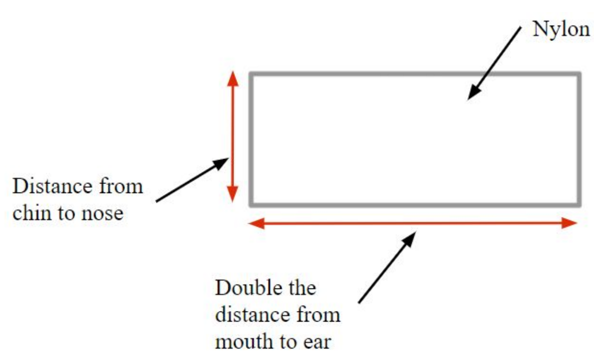
Manufacturing Plan

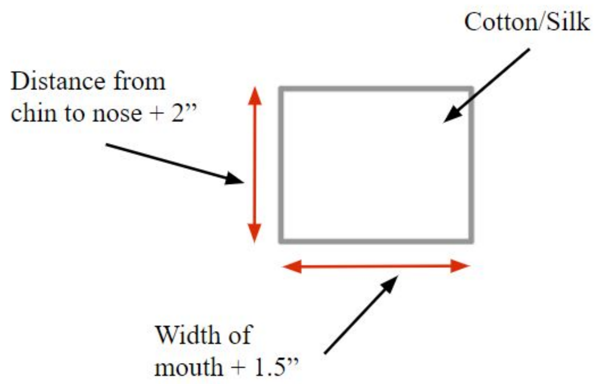
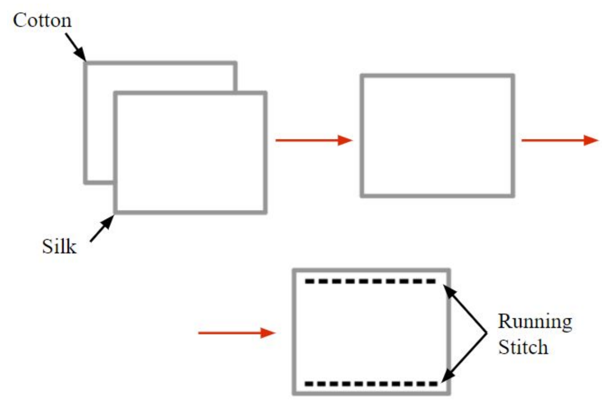
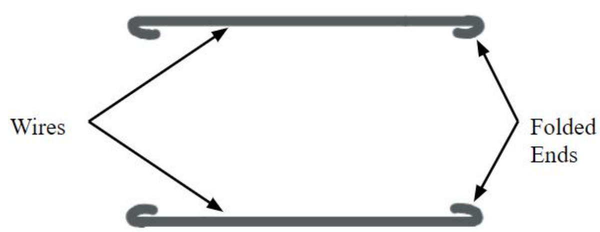
Tools Required:

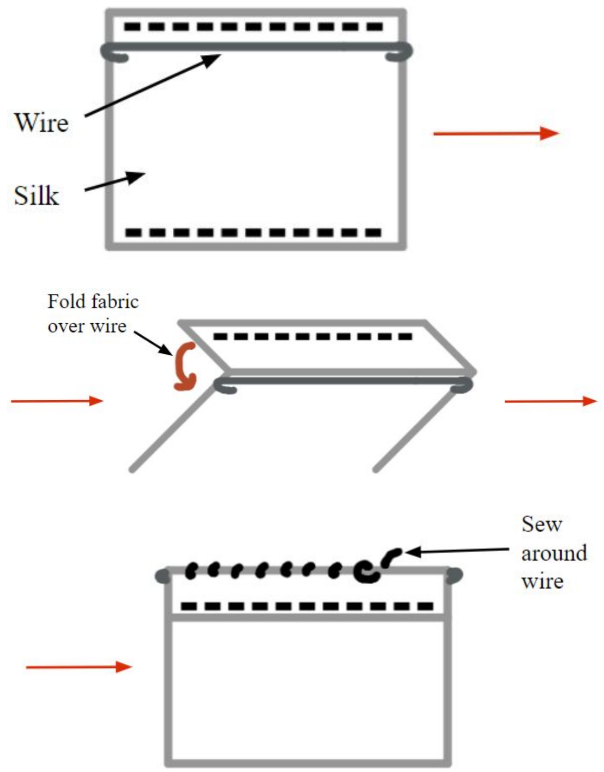
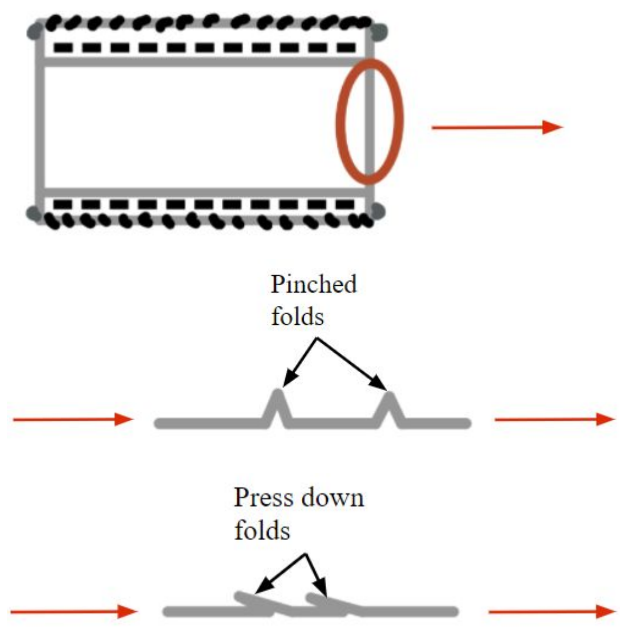
1 pair of utility scissors (or any pair of sharp scissors capable of cutting through fabric)
1 needle
1 12” ruler (or any measurement tool)
4 sewing pins (more can be used as needed to pin fabric together before sewing)
1 marker for marking dimensions on fabric

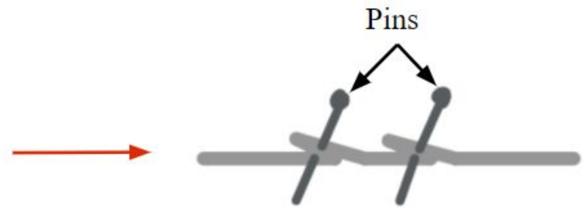
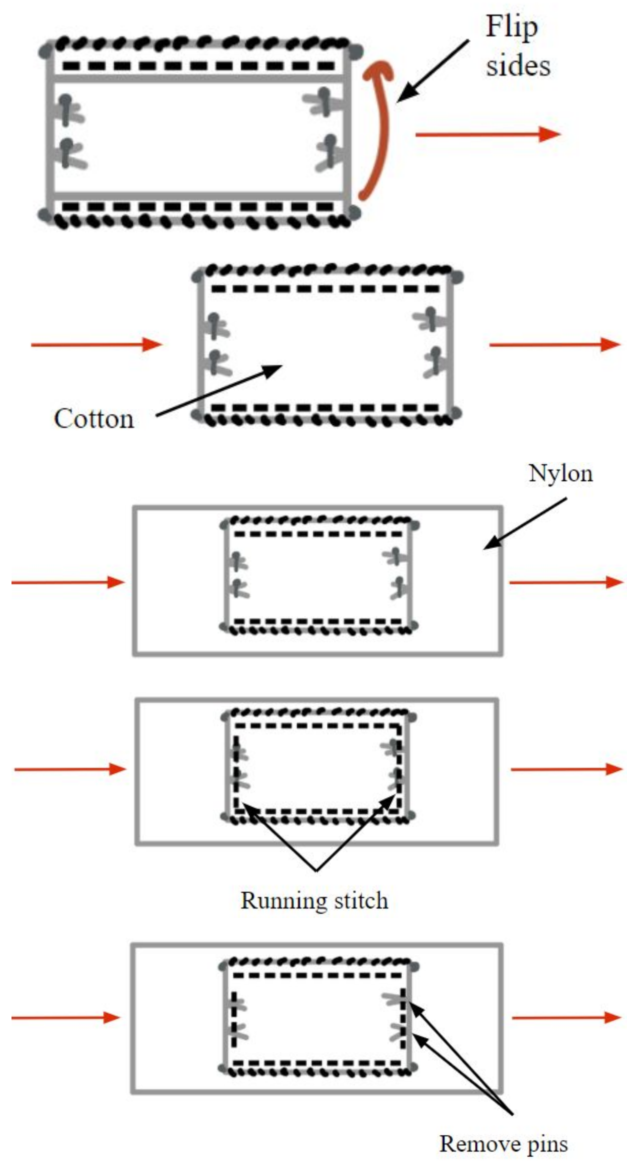
Materials Required:
1’ x 1’ of nylon fabric
1’ x 1’ of tightly woven cotton fabric (i.e. a bed sheet or pillowcase)
1’ x 1’ of silk fabric
1 spool of thread
1’ of aluminum wire (or 1 pipe cleaner)

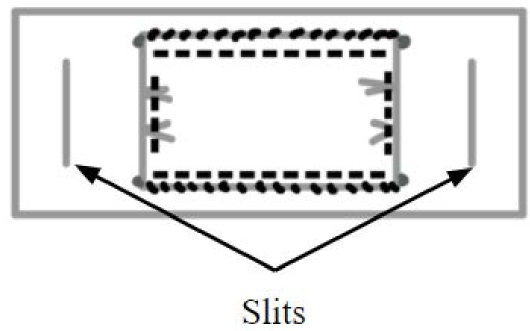
Table A.3. The following table contains the steps required to create the design solution along with pictures clarifying each step.

Steps for Fabrication	**Pictures for Reference**
1. Measure the width of your mouth by holding the ruler horizontally in front of your mouth and recording the approximate width. Measure the distance between the middle of your mouth and the back of your ears by holding the ruler along your cheek. You only need to measure one side of your face. Measure the distance between the bridge of your nose (i.e. the narrow part) and the tip of your chin (i.e. the bottom). Record these three measurements on a piece of paper for future use.	
2. Using your utility scissors, cut a rectangle of nylon fabric with a height equal to the distance between the bridge of your nose and the tip of your chin. Cut the width to be double the distance between the middle of your mouth and the back of your ear.	

3. Using your utility scissors, cut a rectangle of cotton fabric with a height 2" longer than the height of the nylon rectangle cut in the previous step (i.e. 2" longer than the distance between the bridge of your nose and the tip of your chin). Cut the width of the cotton to be a total of 1.5" longer than the width of your mouth as measured in Step 1.	
4. Repeat Step 3 with the silk fabric.	
5. Place the rectangle of cotton directly on top of the rectangle of silk so that all edges line up. The wrong sides of each fabric should be facing one another. Using your needle and thread, sew together the two edges that are slightly longer than the width of your mouth. These are the top and bottom edges. Sew along the edges, within ¼" of each edge. This should create two layers of fabric.	
6. Take your aluminum wire (or pipe cleaner) and hold it up to one of the sewn edges. Using your utility scissors, cut your wire to the length of the edge, adding approximately ½" to the length. Repeat this step for the other sewn edge. Fold each end of both wires by approximately ¼" so you don't get poked by the ends.	

7. Place the first wire along the top edge of the cotton side of the cotton and silk rectangle and fold the fabric over the wire so that the wire is enclosed in the fabric. The fabric should overlap itself by approximately ½” (i.e. the fold should be ½” deep). Then, with your needle and thread, sew along the entire length of the wire into the edge of the fold so that the thread is wrapping around the fabric-enclosed wire. Repeat this step for the other wire on the bottom edge.	
8. Looking at the edges of the cotton and silk fabric that do not have a wire, measure approximately one third of the way down the side edge. With the silk side of the fabric facing you, use your fingers to pinch approximately ¼” of the fabric and fold it back upon itself, forming a pleat. Pin this pleat in place. Measure another one third down the side edge and form another pleat, pinning it in place. Repeat this step on the other side edge.	

	
9. Position your rectangle of nylon fabric on your workspace, with the longer edges appearing horizontal in reference to you. Place the cotton and silk fabric rectangle in the exact center of the nylon rectangle, with the wired edges running parallel to the long edges of the nylon rectangle and the silk side facing the nylon fabric. Using your needle and thread, sew the non-wired edges of the cotton and silk fabric (the edges with the pinned pleats) to the nylon fabric with a running stitch. Remove the pins when complete. The pleats should now be held in place by the running stitch.	

10. Measure approximately 1" from the right side edge (the short edges) of the nylon fabric and cut a slit parallel to the side edge that is 1 inch shorter than the length of the short edge. Make sure to not cut all the way to the top or bottom edges, as this slit will act as your ear holes. Repeat this step on the left side edge of the nylon fabric.	

APPENDIX B: Content from Past Design Reviews

Past Challenges

Design Review 1

In the process of researching and communicating with important stakeholders, certain assumptions were made as to the outcome of project stages. Various roadblocks could be encountered that would cause a need to revise the timeline of the project. Three such important challenges were identified, based off of their higher than typical chance of occurring.

From a research standpoint, the ability to accurately quantify the level of comfort of any mask design will be difficult. Inroads into this process have been completed by studies using an adapted Likert scale, a common-place method that ranks respondents' answers to question statements on a scale of 1 to 6. While this is a powerful tool to judge stakeholders' wants and needs out of a final product, care must be taken to make certain the formulation of useful questions. Additionally, the interpretation of a Likert scale can be subjective to the researcher's biases. After discussion with some stakeholders, considerations for individual pain tolerance could cause some degree of error in the study results. To counteract this, the addition of a question allowing respondents to self-report their pain tolerance could be included.

Successfully conducting tests and collecting feedback from stakeholders and potential users will be vital for the creation of a final product. However, the project timeline has a chance of reaching its end before the development of a design with high fit and filtration metrics is finished. Whether this is a result from the testing side or the fit evaluation process, a change in the final report will be made. Pivoting to turn the research completed into a library of benchmarks and recommendations will still allow for a successful project outcome. The slow start of this project happened primarily due to inexperience in collaborating and gathering data together in this way. Creating a credible guide as well as recommendations for the start of future studies will still have a positive impact.

One of the more severe challenges that could be encountered is the possibility of any and all testing labs on North Campus becoming inaccessible due to timing conflicts or a further shutdown of campus due to a spike in COVID-19 cases. Research into various combinations of materials and their resulting filtration efficiency is a sizable part of the current project plan. Without an existing setup to use, some progress could be made into the team creating a scaled-down testing apparatus for temporary use. Through meetings with Professor Clack and Professor Gamba, some understanding of their design could be recreated. However, the brains of their setup, the small particle sensors, would be prohibitively expensive for the current ME450 team budget if they cannot be borrowed. Therefore, the most likely option for the project plan would be to shift the focus away from testing and towards mask design and comfort heuristics.

Design Review 2

In the process of researching and communicating with important stakeholders, certain assumptions were made as to the outcome of project stages. Various roadblocks could be encountered that would cause a need to revise the timeline of the project. Similar to Design Review 1, three new challenges were identified that the team may encounter.

From a research standpoint, the ability to accurately quantify the level of comfort of any mask design will be difficult. Inroads into this process have been completed by studies using an adapted Likert scale, a common-place method that ranks respondents' answers to question statements on a scale of 1 to 6. While this is a powerful tool to judge stakeholders' wants and needs out of a final product, care must be taken to make certain the formulation of useful questions. Additionally, the interpretation of a Likert scale can be subjective to the researcher's biases. After discussion with some stakeholders, considerations for individual pain tolerance could cause some degree of error in the study results. To counteract this, the addition of a question allowing respondents to self-report their pain tolerance could be included. A comfort priority survey has been sent out in its initial stages to a small group of people for feedback. The team needed to do this to gauge possible oversights in the formation of questions. This survey will help the team further understand the different metrics of comfort and determine more specific questions to ask in a comfort survey that seeks feedback regarding a prototype. Overhauling the comfort priority survey based on feedback, and finally sending it out in its final version, will continue to be a challenge for the next two weeks.

Successfully conducting tests and collecting feedback from stakeholders and potential users will be vital for the creation of a final product. However, the project timeline has a chance of reaching its end before the development of a design with high fit and filtration metrics is finished. Whether this is a result from the testing side or the fit evaluation process, a change in the final report will be made. Pivoting to turn the research completed into a library of benchmarks and recommendations will still allow for a successful project outcome. The slow start of this project happened primarily due to inexperience in collaborating and gathering data together in this way. Creating a credible guide as well as recommendations for the start of future studies will still have a positive impact.

One of the more severe challenges that could be encountered is the possibility of any and all testing labs on North Campus becoming inaccessible due to timing conflicts or a further shutdown of campus due to a spike in COVID-19 cases. Research into various combinations of materials and their resulting filtration efficiency is a sizable part of the current project plan. Without an existing setup to use, some progress could be made into the team creating a scaled-down testing apparatus for temporary use. Through meetings with Professor Clack and Professor Gamba, some understanding of their design could be recreated. However, the brains of their setup, the small particle sensors, would be prohibitively expensive for the current ME450 team budget if they cannot be borrowed. Therefore, the most likely option for the project plan would be to shift the focus away from testing and towards mask design and comfort heuristics. Since the completion of Design Review 1, the team has secured access to Professor Mirko Gamba's testing apparatus for short term use this semester, eliminating this challenge from being considered. However, use of the rig will require more research as the atmosphere and conditions within the rig must be manipulated properly for the testing to prove fruitful. Therefore, one of the more significant challenges the team is facing is an identification of certain variables to factor in. Room temperature, relative humidity, particle size, and particle speed are a few such variables that will have great impact on the final results. Detailed analysis will be required to determine the range of values to go forward. Should access to testing be revoked in the future, this research will still serve its purpose in informing the final design phase this semester.

One last challenge facing the team is the precise testing of functional fit of mask designs. While the filtration testing is clearly defined in the project plan, the next step will be to create a system to determine how geometry of possible designs influences air flow. This has been outlined above in the testing plan.

Design Review 3

In the process of researching and communicating with important stakeholders, certain assumptions were made as to the outcome of project stages. Various roadblocks could be encountered that would cause a need to revise the timeline of the project. Similar to Design Review 2, four new challenges were identified that the team may encounter.

More research and fact-checking will be necessary to finalize the method for sizing the mask and determine how precise facial measurements need to be. As primary end uses may not have a technical background or precise measuring equipment, the mask needs to be able to be correctly sized without precise measurements. Similar in vein, another challenge that deals directly with mask creation is the improvement of prototyping speed. With the potential that end users may not have access to sewing machines and the fact that sewing machines were not able to be accessed by the team, hand-sewing is required. Due to the lack of experience by the team with hand sewing, each prototype takes a large amount of time to create. As more prototypes need to be made for testing, trimming down the amount of time it takes to make each prototype is essential.

Within a matter of days, the team expects to begin work with Professor Gamba and his testing apparatus. Due to an unforeseen medical emergency, one of the members who completed training and was certified by the university to access the building on campus has fallen ill. Making sure to introduce a new member of the team to the training and certify this change with Professor Gamba or one of his graduate students has proved to be a short term challenge with the extra level of regulation caused by COVID-19. Lastly, the transfer of materials and prototypes within the team is a challenge to be faced, due to the concern of the spread of the virus. Particular care is needed to minimize potential exposure, due to none of the team members living in the same house or location. Further restrictions by the State of Michigan regarding the mid-November stay-at-home order also have caused some disruption. Any possible testing on North Campus has been narrowed to a two-day window before buildings begin to shut down.

Past Project Plan

Design Review 1

A project plan was developed to outline the tasks that must be completed before Design Review 2. These tasks can be organized into three categories: 1) Continue to verify requirements and specifications; 2) Develop a testing plan; 3) Ideate and generate concepts. Figure B.1 contains the project plan organized in a Gantt chart. The resources required and team members responsible for each task was omitted from the Gantt chart for the sake of readability and are included in Figure B.2.

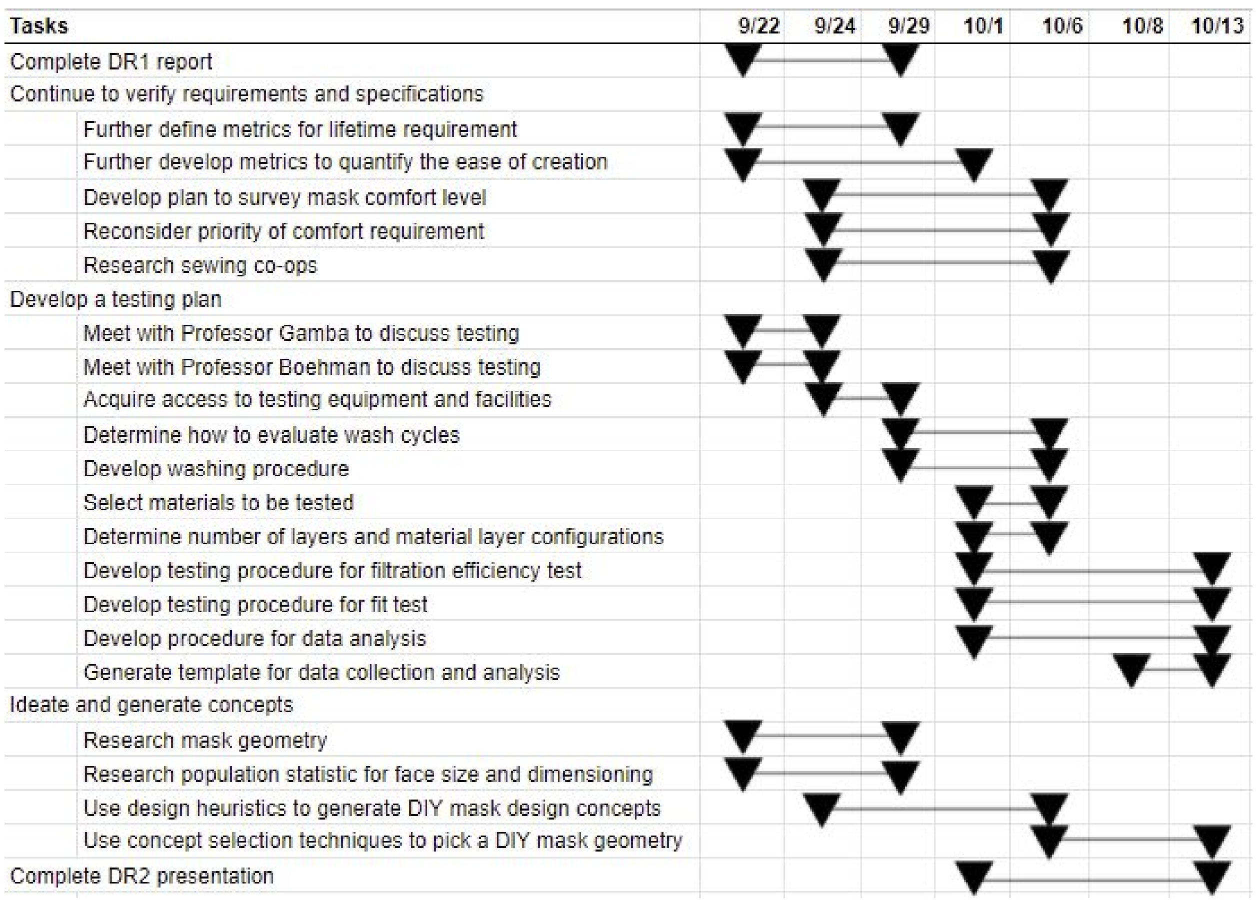


Figure B.1. The above figure contains the Gantt chart used to outline the project plan. The Gantt chart lists different tasks and the corresponding timeline for each task.

Tasks		Team Member	Resources
Complete DR1 report		All members	Literature
Continue to verify requirements and specifications			
	Further define metrics for lifetime requirement	JT	Literature
	Further develop metrics to quantify the ease of creation	All members	Literature
	Develop plan to survey mask comfort level	All members	Literature
	Reconsider priority of comfort requirement	All members	Literature, Stakeholders
	Research sewing co-ops	JG, NK	Literature
Develop a testing plan			
	Meet with Professor Gamba to discuss testing	All members	Video chatting platform
	Meet with Professor Boehman to discuss testing	All members	Video chatting platform
	Acquire access to testing equipment and facilities	AB	Email
	Determine how to evaluate wash cycles	JG, NK	Literature
	Develop washing procedure	JG, NK	Bucket, washboard
	Select materials to be tested	NK, AS	Literature
	Determine number of layers and material layer configurations	NK, AS	Literature
	Develop testing procedure for filtration efficiency test	AB, JT	Mask testing apparatus
	Develop testing procedure for fit test	AB, JT	Mask testing apparatus
	Develop procedure for data analysis	AB, AS	MATLAB/Microsoft Excel
	Generate template for data collection and analysis	AB, AS	Literature, MATLAB/Microsoft Excel
Ideate and generate concepts			
	Research mask geometry	JG, JT	Literature
	Research population statistic for face size and dimensioning	JG, JT	Literature
	Use design heuristics to generate DIY mask design concepts	All members	Literature
	Use concept selection techniques to pick a DIY mask geometry	All members	Literature, Mask testing apparatus
Complete DR2 presentation		All members	Literature

Figure B.2. The above figure displays the information omitted from the Gantt chart. Each task to be conducted between Design Review 1 and Design Review 2 has team members assigned to the task and resources that may be required to complete the task.

Within continuing to verify requirements and specifications, there is a need to further define metrics for the lifetime requirement. The lifetime requirement is currently specified as the mask being able to sustain greater than 20 uses. This specification was determined by comparing the number of uses identified with different mask decontamination techniques as found in literature (Oh, 2020; Centers for Disease Control and Prevention, 2020f). However, lifetime depends on the rigor of the decontamination process between uses. With a rigorous decontamination cycle, the number of uses could potentially be less than 20. Additionally, there is a need to further develop metrics for quantifying the ease of creation of the mask. The amount of time and number of steps for creation does not guarantee satisfaction of the ease of creation requirement. A more in depth literature review will be conducted on the tools needed to construct most DIY masks and the amount of time each mask takes to create in order to complete this task. Lastly, there is a need to develop a plan to survey mask comfort level. The Likert scale outlined in the engineering specifications for the comfort requirement requires prototype masks to be sent to low resource areas (Purdy, 2019). However, sending prototypes overseas can be infeasible given the short timeline of the project. Therefore, a plan needs to be developed to send prototypes to potentially low resource settings in the US for feedback. If a different and more feasible metric for comfort is discovered, the Likert scale will be replaced.

Upon receiving feedback regarding Design Review 1, both Professor Gordon and Professor Sienko suggested that the priority of mask comfort be re-evaluated. Since adoption of the DIY mask design by the general public hinges on how comfortable the mask is, the comfort requirement should potentially be of higher priority. Either a survey needs to be sent out or an interview needs to be scheduled with relevant stakeholders to determine whether or not comfort should be held as a higher priority than the other requirements. Professor Gordon also recommended that research be done on sewing co-ops in low resource countries like Ghana. Sewing co-ops are groups of people who sew items together. People in these co-ops are typically of higher skill level but may require a lower cost and a lower creation time. Research needs to be done into sewing co-ops to determine a potential re-evaluation of requirements.

Developing a testing plan is essential in ensuring that the designed DIY mask is tested effectively for its filtration efficiency and fit. The first part of this task is to meet with both Professor Gamba and Professor Boehman. Professor Gamba's lab has a testing apparatus that can test the filtration efficiency of masks using aerosols and a particle sizer (SMPS) (Herek, 2020). Having access to the lab would allow Team 16 to test the DIY masks. If access to Gamba's lab cannot be provided, a DIY testing apparatus will be constructed. Professor Boehman offered to loan his SMPS for use in a DIY testing apparatus (Andre, 2020). The next sub-tasks are determining how to evaluate wash cycles and developing a washing procedure. When interviewing the KNUST Student Team, it was learned that the current method for decontaminating DIY masks entails washing them by hand in tepid water with laundry detergent and then hanging them out to dry in the sun (KNUST Team, 2020). Since it is hard to quantify and directly recreate the wear and tear on the masks during the hand-washing cycle, further research is needed in regards to the washing procedure in Ghana. Additionally, each wash cycle will need to be evaluated to ensure that there was sufficient wear and tear on each mask. The next task is to select potential mask materials to test from the working list of materials available in low resource settings. Once materials are selected, different layer configurations need to be generated so masks of different material layers can be tested.

The final sub-tasks related to developing a testing plan involve creating testing procedures for filtration efficiency tests and fit tests. Once this is done, a procedure for conducting data analysis and a template for data collection will be created to streamline the data collection process. There is a chance that Professor Gamba will be testing the team's samples, so in order to reduce any work that must be done for us, the testing procedures and data collection will need to be as fast and efficient as possible.

Ideation and concept generation is the final task category on the Gantt chart. Before testing can occur, various concepts for DIY masks need to be generated. Design heuristics will be used to aid in the ideation process. Additionally, mask geometry and sizing needs to be researched in order to generate feasible mask designs. This task will be completed by studying anthropometric data from various low resource areas around the world.

Design Review 2

Another project plan was developed to outline tasks to be completed between Design Review 2 and Design Review 3. The necessary tasks can be split into seven categories: 1) Connecting with more contacts; 2) Re-prioritizing comfort and further developing aspects of comfort; 3) Prototyping masks; 4)

Testing for mask fit; 5) Developing preliminary solution concepts; 6) Testing for filtration efficiency of materials; 7) Testing for mask comfort. Figure B.3 contains a Gantt chart that specifies each task and the respective timeline for each task, with Design Review 3 being on 11/10. Figure B.4 contains the resources required and the team members responsible for each task.

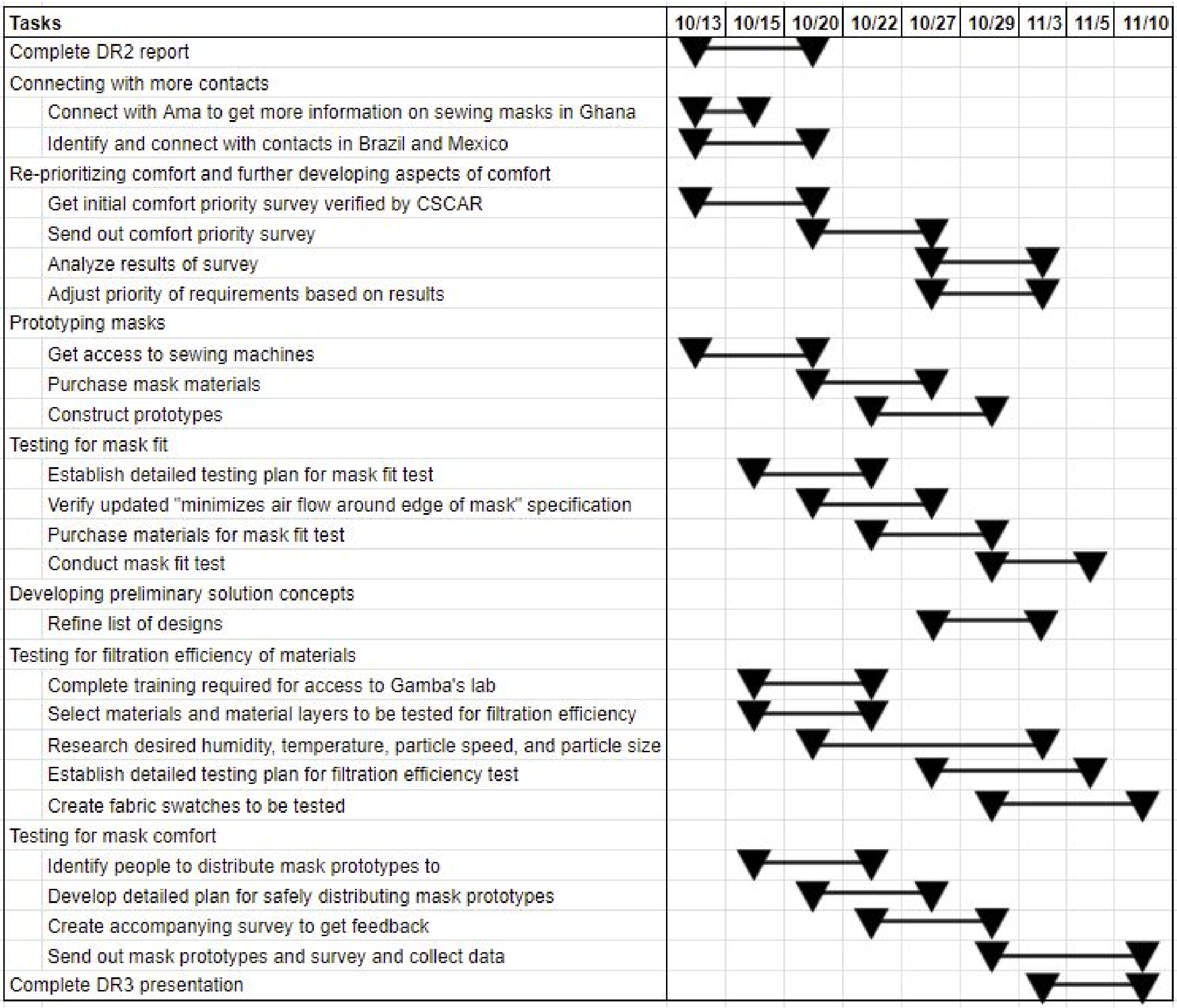


Figure B.3. The above figure contains the Gantt chart outlining tasks to be completed between Design Review 2 and Design Review 3 with their respective timeframe.

Tasks		Team Member	Resources
Complete DR2 report		All members	Literature
Connecting with more contacts			
	Connect with Ama to get more information on sewing masks in Ghana	AB	Email, Stakeholders
	Identify and connect with contacts in Brazil and Mexico	AB, AS	Email, Stakeholders
Re-prioritizing comfort and further developing aspects of comfort			
	Get initial comfort priority survey verified by CSCAR	All members	Email
	Send out comfort priority survey	All members	Google Forms, Stakeholders
	Analyze results of survey	All members	Google Forms, Excel
	Adjust priority of requirements based on results	All members	Google Docs
Prototyping masks			
	Get access to sewing machines	JT, JG	Email
	Purchase mask materials	NK	Literature
	Construct prototypes	All members	Mask Materials, Sewing Machines
Testing for mask fit			
	Establish detailed testing plan for mask fit test	AS, AB	Literature, Stakeholders
	Verify updated "minimizes air flow around edge of mask" specification	AS	Reqs and Specs
	Purchase materials for mask fit test	NK	Google Docs
	Conduct mask fit test	AB, JT	Fit Test Materials
Developing preliminary solution concepts			
	Refine list of designs	All members	Literature, Test Results
Testing for filtration efficiency of materials			
	Complete training required for access to Gamba's lab	AB, NK	Email, Training Module
	Select materials and material layers to be tested for filtration efficiency	All members	Literature
	Research desired humidity, temperature, particle speed, and particle size	JG, JT	Literature
	Establish detailed testing plan for filtration efficiency test	AB, NK	Literature, Stakeholders
	Create fabric swatches to be tested	AB, AS	Materials, Sewing Machines
Testing for mask comfort			
	Identify people to distribute mask prototypes to	AS, AB	Literature, Stakeholders
	Develop detailed plan for safely distributing mask prototypes	All members	Literature, Stakeholders
	Create accompanying survey to get feedback	JT, JG	Google Forms
	Send out mask prototypes and survey and collect data	All members	Stakeholders, Google Forms
Complete DR3 presentation		All members	Literature

Figure B.4. The above figure contains the tasks as outlined in the Gantt chart, the team members assigned to each task, and the expected resources required to complete each task.

In connecting with more contacts, a community member in Ghana named Ama was identified by Caroline Soyars (Ama, 2020). Ama makes face masks for her community and was able to provide information regarding the cost, time required, and materials used to make each mask. Contacts in Brazil and Mexico are also in the process of being identified to provide more information regarding the creation and use of masks in other low resource settings.

Re-prioritizing comfort and further developing aspects of comfort is currently in the process of being completed after receiving feedback expressing concern for the comfort of the masks being the lowest priority stakeholder requirement. A survey has been developed that asks survey-takers to rank the ability of their own mask to protect them and others from COVID-19 with various aspects of comfort, such as breathability of the mask, tightness of the mask to one's face (i.e. too loose or too tight), potential skin irritation caused by the mask, and potential sweat build-up on one's face caused by the mask. This survey has been sent out to close friends and family members in a pilot run and, once verified by either Consulting for Statistics, Computing, and Analytics Research (CSCAR) or the Survey Research Center (SRC) at the University of Michigan, will be sent out to a larger audience of university students and students in ME 450 to allow for a deeper understanding of mask comfort and a reprioritization of the comfort requirement.

To prototype the preliminary mask designs, sewing machines need to first be secured. ME 450 has a sewing machine available in the X50 shop for use by reservation. Additionally, the Ann Arbor District Library has NQM 2016 sewing machines available to borrow. Securing sewing machines from the public library will likely be the priority, as taking a sewing machine home will allow for more flexibility in prototyping. If neither of these options work, the team has family members that can loan sewing machines. Once sewing machines are secured for prototyping, mask materials will be purchased and prototypes will be constructed individually by each teammate. Due to the high volume of prototypes that will be produced, an effort will be made for each teammate to contribute to prototyping.

In testing prototype masks for their ability to minimize air flow around the edges, the original testing plan found in literature involved using specialized equipment to measure the concentration of aerosol particles inside and outside of the mask and then take the ratio to determine the fit factor (Davies, 2013). However, the required equipment is both expensive and unavailable. Therefore, a test was outlined by the team to connect a vacuum through the back of both a male and female mannequin head to simulate a steady, constant velocity breath. A mask would be placed over the mouth of the mannequins and a wind speed meter would be used to measure the speed of the air coming out of the edge of the masks. Ideally the wind speed around the edges of the mask would be zero m/s with a perfect fit. While the logistics of this test still need to be further planned, the “minimizes air flow around edge of mask” specification has already been adjusted to be in terms of wind speed since fit factor will no longer be used as a metric. Additional verification is needed to confirm this specification change beyond the verification received from Professor Clack (Herek, 2020). Once this is completed, materials can be purchased and the test can be conducted.

Within developing preliminary solution concepts, the number of designs prototyped will be reduced based on redundancy and results from the mask fit test. Since it will not be feasible to continue through the rest of the project with 11 different designs, refining the list to two or three concepts will allow for more focused development and more feasible testing.

The next test that will be conducted is the filtration efficiency test. In Professor Gamba’s lab, there is a testing apparatus that takes in certain ambient conditions (i.e. ambient temperature, particle size, particle speed, humidity) and then sprays an aerosol at a swatch of fabric (Mirko, 2020). The concentration of particles is then measured on each side of the fabric swatch to determine the filtration efficiency of the material. Access to this apparatus has been secured, and training needs to be completed through the university to safely access the lab and learn about COVID-19 safety procedures. As training is occurring, different materials and layering combinations will be selected to test. The ambient temperature, humidity, particle size, and particle speed each need to be selected to simulate ambient conditions in low resource settings and the correct size and speed of COVID-19 particles in aerosol form. Once materials and conditions are selected, a detailed testing plan will be constructed to maximize testing efficiency in the very short amount of available lab time. Fabric swatches will then be constructed to be tested after Design Review 3.

Lastly, a plan to test mask comfort needs to be developed. Due to the safety risks associated with distributing mask prototypes during the COVID-19 pandemic, prototype distribution needs to be planned and will likely only involve housemates and family members. A plan needs to be developed to safely distribute the mask prototypes. An accompanying survey then needs to be developed to allow users to provide organized feedback regarding various aspects of the comfort of the mask. The two or three mask designs chosen for distribution will then be sent out along with the survey to selected people so that prototypes can be assessed for their comfort. Prototypes will be assessed using a Likert scale (1-6) based on three comfort metrics: comfortable fit to face, temperature, and breathability (Purdy, 2019). However, additional metrics may be included depending on the results of the initial mask comfort priority survey.

Design Review 3

Another project plan was developed to outline tasks to be completed between Design Review 3 and the Final Report. The necessary tasks can be split into six categories: 1) Conduct Mask Filtration Efficiency Test; 2) Conduct Use Test; 3) Conduct Mask Comfort Test; 4) Verify Stakeholder Requirements; 5) Finalize Design; 6) Complete the Course. Figure B.5 below contains a Gantt chart that specifies each task and the respective timeline for each task, with the Final Report being due on 12/8. Figure B.6 contains the team members responsible and the resources required for each task.

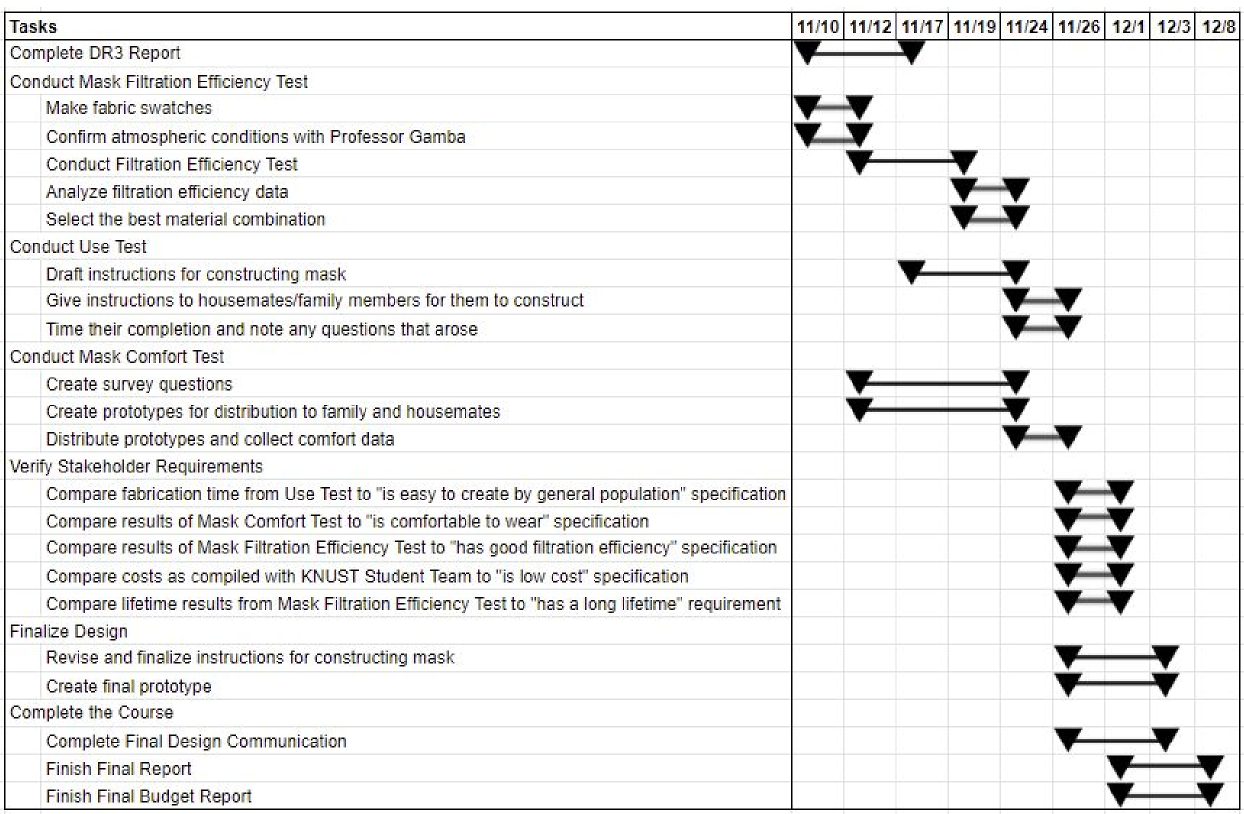


Figure B.5. The above Gantt chart outlines the tasks that must be completed before the end of the project and a timeline of when they will be completed.

Tasks	Team Member	Resources
Complete DR3 Report	All members	Literature
Conduct Mask Filtration Efficiency Test		
Make fabric swatches	AB, AS	Sewing equipment, fabric
Confirm atmospheric conditions with Professor Gamba	AB, AS	Literature, email
Conduct Filtration Efficiency Test	AB, AS	Gamba's lab, testing apparatus
Analyze filtration efficiency data	JG, NK	Excel, MATLAB
Select the best material combination	All members	Data
Conduct Use Test		
Draft instructions for constructing mask	JT, JG, NK	Literature, prototypes
Give instructions to housemates/family members for them to construct	All members	Sewing equipment, fabric
Time their completion and note any questions that arose	All members	Stopwatch
Conduct Mask Comfort Test		
Create survey questions	AB, JT	Literature
Create prototypes for distribution to family and housemates	AB, AS, JT	Sewing equipment, fabric
Distribute prototypes and collect comfort data	All members	Prototypes, survey
Verify Stakeholder Requirements		
Compare fabrication time from Use Test to "is easy to create by general population" specification	AB	Data
Compare results of Mask Comfort Test to "is comfortable to wear" specification	JG	Data
Compare results of Mask Filtration Efficiency Test to "has good filtration efficiency" specification	AB, AS	Data
Compare costs as compiled with KNUST Student Team to "is low cost" specification	NK, JT	Data
Compare lifetime results from Mask Filtration Efficiency Test to "has a long lifetime" requirement	AB, AS	Data
Finalize Design		
Revise and finalize instructions for constructing mask	All members	Literature, data
Create final prototype	AB, AS, JT	Sewing equipment, fabric
Complete the Course		
Complete Final Design Communication	All members	Literature, prototypes
Finish Final Report	All members	Literature, prototypes
Finish Final Budget Report	All members	Literature, bill of materials

Figure B.6. The above figure contains the tasks as outlined in the Gantt chart, the team members assigned to each task, and the expected resources required to complete each task.

In conducting the Mask Filtration Efficiency test, the fabric swatches to be tested will be created. Two fabric swatches will be made for each material combination. One of the two for each combination will be washed 20 times to simulate 20 uses. While these are being made, the atmospheric conditions of temperature and humidity level will be confirmed with Professor Gamba along with particle size and particle speed (Mirko, 2020). Once confirmation is received and a date is set to go into the lab, the test will be conducted. Next, the data will be analyzed to determine which fabric swatch has the best filtration efficiency. This fabric combination will then be used as the filtering material in the final design.

In conducting the Use Test, instructions will be drafted regarding how to make the mask. The instructions will then be given to housemates and family members for them to construct. The amount of time it takes them to complete the mask will be timed and compared to the “is easy to create” engineering specification. Additionally, notes will be recorded by the team regarding feedback so improvements can be made to the instructions.

In conducting the Mask Comfort Test, a survey will be created that asks wearers to rate the mask using a six-point Likert scale on the following three metrics: comfortable fit to face, temperature, and breathability (Purdy, 2019). While the survey is being generated, prototypes will be constructed by the team for housemates and family members to try on. There will be one prototype created for each wearer, and each prototype will be destroyed after the test is conducted. Upon completing this report, the survey has been created and used in the Mask Comfort Test completed as part of the engineering analyses.

After all of the data has been collected from the Mask Filtration Efficiency Test, Use Test, and Mask Comfort Test, the fabrication time, Likert scores, and filtration efficiency will all be compared to the corresponding engineering specifications to determine whether or not the final solution meets the requirements set by the stakeholders. Additionally, the data regarding mask filtration efficiency degradation across subsequent washes will be analyzed to determine whether or not the "has a long lifetime" requirement is verified. Lastly, cost estimates gathered in conjunction with the KNUST Student Team regarding the price of materials in Ghana will be used to determine verification of the "is low cost" specification (KNUST, 2020).

In finalizing the design, the instructions for creating the mask will be adjusted based on feedback from the Use Test. A final prototype will then be made to be displayed at the Design Expo. Finally, the course will be completed by submitting the Final Design Communication, Final Report, and Final Budget Report.

Past Next Steps

Design Review 1

Upon completion of current research and data collection, several new subsections of milestones will become available. With the help of Professor Sienko, the search for additional stakeholders will continue through contacting Global REACH at the University of Michigan as well as ENT or respiratory doctors. Analyzing responses from the KNUST team in Ghana will give some insight into how to refine the team's search. Testing will be able to begin as interactions with staff in the Engineering college also begin. Discussing goals and schedules with Professor Gamba will give the opportunity to secure time slots for the team's use. While testing occurs, determining useful metrics for geometric tolerances and fit to face will be just as vital. Population statistics, as well as research into the creation of standardized mask sizes are top candidates to start looking into. One of the more conceptual steps the project will need to take is one involving ideation and generation of what qualities the eventual design will possess. Use of out-of-the-box tools such as Design Heuristics, LLC's flashcards could offer new approaches to the project that haven't been thought of yet.

Design Review 2

In regards to stakeholders, it is important to gather more information on how DIY masks are made in other low resource settings. To assist in this, the team is connecting with a contact in Ghana, named Ama, who's family houses students from the University of Michigan during international programs. Ama currently makes DIY masks for her community and has a cousin who works in textiles that may be willing to talk with us. Contacts in Brazil and Mexico will also be identified to learn more about the mask making and mask wearing culture in those regions. In regards to the prioritization of comfort, the team is currently looking at the Center for Statistics, Computing and Analytical Research (CSCAR) and the Survey Research Center (SRC) for help in validating a survey regarding different facets of mask comfort. A meeting with at least one of these groups will be set up and the survey will be revised accordingly before it is sent out to a larger group for feedback. The team will also begin purchasing materials for prototyping and planning the mask fit test.

Design Review 3

With the successful completion of the third Design Review presentation, the team has identified four steps that will be focused on in the immediate future. These were chosen due to either the time constraints built into their completion, or because of the logical continuation from milestones completed prior to Design Review 3. Of primary importance for the project is continuing to send out the Comfort Priority Survey to as many recipients as possible. Increasing the sample size as well as the diversity of respondents will strengthen the study's results for use. Identifying potential new groups or paths to send the survey out quickly will be vital. Within the next week, the team hopes to finish the Mask Filtration Efficiency Test with the help of Professor Gamba. The team will need to discuss some basic information about temperature and humidity, plus a handful of other variables, with Professor Gamba in order to get useful results. Using these variables will allow Professor Gamba's rig to simulate a more useful environment. The last two steps the team must complete next concern the creation of prototypes. Several must be made to hand out to friends and family for the Mask Comfort Test to get their opinions on the comfort metrics of comfortable fit to face, breathability, and temperature. Lastly, work is going to be completed on the instructions that will be given out to stakeholders for their own DIY mask creation for the Use Test and at the end of the project. The layout and wording of each step will have to be considered in a variety of ways, in order to avoid any confusion that could arise.

Past Incorporation of Presentation Feedback

Design Review 1

During the presentation feedback session with Professor Sienko, the team assembled a list of changes that could be made to better augment future research and presentations to be more easily received by others. The citation of sources in the presentation didn't always clearly indicate which information it was referring to. Some sources were also not cited at all. To remedy this, whole page citations will be moved up into the headers for future presentations. The form of the citation will be changed, too, from simple numbers referring to an index of sources to an author/year format for quicker recognition.

Some confusion came from the problem statement listed at the start of Design Review 1. Professor Sienko advised the team to consider creating a graphic showing the evolution of the statement as new stages of the project were revised along the way. Also, the slide in Design Review 1 regarding benchmarking reporting caused confusion since the benchmarks were not separated into sections (such as testing, mask design, research). Creating several slides, each showing one aspect of benchmarking, will prove to be more efficient for conveying information.

Some of the most useful feedback came regarding stakeholders, challenges, and requirements. Creating a system detailing the level of engagement of current stakeholders will show progress made in communications more clearly. Adding more short-term and medium-term challenges will give more information about what hurdles the team will deal with in the near future. Modification of some project requirements was recommended, too. Specifically, the “Easy to Create” requirement should have had a deeper level of explanation regarding the manufacturing process of masks. Creating goals for who will be creating a mask (whether it be an individual or a small cooperative) and the type of tools needed to complete the process will be needed.

Design Review 2

Similar to meetings following the presentation of the team’s Design Review 1, the feedback received from Professor Sienko was very useful to advise the creation of the report and potential leads for the next few weeks. Presentation feedback received after Design Review 1 is included in Appendix B (page 45). One of the main technical communication critiques on the presentation was the poor citations concerning existing research into mask design benchmarking. While the four examples used accurately showcased the wide range of different features that consumers could make or purchase, more information about the statements made about these examples was needed. In order to prevent an appearance of subjectivity, providing the sources for benefits and drawbacks of each benchmark will be required in the future.

The other main discussion that arose in the feedback session concerned the brief mention that the team was looking to distribute mask samples to potential users for feedback. Professor Sienko was helpful in commenting on the inherent risk that could accompany such a process, due to potential liabilities if any prototypes were kept in use after the study ended. Making sure the team was on the same page for this topic gave some new ideas on how the process of getting comfortability metrics from stakeholders would proceed. The institutional review board at the University of Michigan for Health Sciences and Behavioral Sciences (HSBS) would possibly serve as an overseer for any such study to take place. It will be important to note that the chance of the team being able to reach this milestone before the semester’s end is uncertain as of now.

Design Review 3

Similar to meetings following the presentation of the team’s Design Review 2, the feedback received from Professor Sienko was very useful to advise the creation of the report and potential leads for the next few weeks. Presentation feedback received after Design Review 2 is included in Appendix B ~~(pages 57-67).~~

One of the first suggestions the team was given was to consider the inclusion of cost estimates into the presentation. While this could be a great metric for testing the viability of the project, the focus could be placed on how various regions of the world could influence this. Different countries around the world have vastly different costs of living, and this would directly factor into how expensive each DIY mask would be. Specific low-resource countries could be targeted, such as Ghana and Nicaragua.

Additional clarity could be included when detailing the testing methods the team conducted. A quick alteration would be to include visual representations of the tasks performed, either by using graphs or pictures showing the setup of each test. Doing so would increase the reliability of the findings, as well as allow future testing to be done with a reasonable understanding of how to prepare. The team also received the suggestion to go into the detail of possible repetitions of testing to ensure the validity of any results and to make sure no error or outlier was falsely reported. Including a list of factors that could influence these results could provide extra security that the tests could be trusted to a higher level when creating material for the final report.

Past Testing Plan

To test the mask designs and verify satisfaction of requirements, three tests have been developed: 1) Material Filtration Efficiency Test; 2) Mask Fit Test; 3) Mask Comfort Test. Table 8 below contains the name of each test along with the framing question that would be answered by each test.

Table B.1. The following table contains the three different tests that will be performed during the project and the questions that guide each test.

TEST	GUIDING QUESTIONS
Mask Filtration Efficiency Test	Which combination of mask materials can filter out the greatest amount of particles? How does number of uses and washes impact filtration efficiency?
Mask Fit Test	Which mask design minimizes the amount of air flowing around the edge of the mask? What components of each mask may contribute to better fit? Where does the most air flow occur?
Mask Comfort Test	Which mask design is the most comfortable? What about the masks may make them comfortable?

The Material Filtration Efficiency Test will be conducted after Design Review 3 using a filtration efficiency testing apparatus in Professor Mirko Gamba's lab (Mirko, 2020). Access to this lab was acquired after meeting with Professor Gamba and discussing both the testing apparatus and the project. To conduct the test, a fabric swatch needs to be sealed in a holder inside of an enclosed tube. Then, conditions like temperature, humidity, particle speed, and particle size need to be inputted into the apparatus to match atmospheric conditions and the size and speed of a coronavirus particle as it travels through the air. An aerosol matching the particle size and speed of coronavirus is then sprayed down the sealed tube and through the fabric swatch. Particle sizers measure the concentration of particles both upwind and downwind of the fabric swatch. The filtration efficiency is then calculated by comparing the amount of particles that passed through the fabric to the amount that were filtered out by the fabric. Multiple types of fabrics with varying layers and varying number of washes (to simulate multiple uses) will be tested to determine which combination has the best filtration efficiency. The fabric swatch with the best efficiency will be used in the final mask design.

The Mask Fit Test will be conducted before Design Review 3. The original planned fit test was based on literature found in which a particle sizer and other specialized equipment measured the concentration of particles both inside and outside of the mask and then calculated the ratio of the concentrations (referred to as the fit factor) (Davies, 2013). However, the required equipment is both expensive and unavailable. Therefore, a test was designed by the team to measure the air flow around the edge of the mask. A hole will be drilled through the mouth-area of both a small and large mannequin head. This hole will be drilled through the entirety of the head, and a vacuum will be attached to the back to blow outwards and simulate an outward breath of known air speed. A mask will be placed on the mannequin heads over the mouth areas to simulate someone wearing a mask. A wind speed meter, which will be borrowed from the X95 lab or purchased online, will then be used to measure the wind speed of any air flowing around the edge of the mask by holding the wind speed meter next to all of the edges. Ideally, the wind speed around the edge of the mask should be zero m/s because there should not be any air flow with a perfectly fitted mask. This air speed assumption has already been verified by Professor Herek Clack, who emphasized that any air flow around the edge deems the mask ineffective at protecting the user against COVID-19 (Herek, 2020). The “minimizes air flow around edge of mask” specification has been updated to an air speed of 0 m/s to reflect this.

The Mask Comfort Test will take the form of a survey. Once prototypes have been refined down to only two or three options, multiple copies will be made and then distributed to housemates and close family members for them to try on. An accompanying survey will be developed based on the study found in literature in which a 1-6 Likert Scale was used to rate mask comfort based on three comfort metrics: comfortable fit to face, breathability, and temperature (Purdy, 2019). The survey will likely be adapted to further explain metrics and include more metrics that define comfort (i.e. potential skin irritation and tightness). Those who receive prototypes will be asked to complete the associated survey so that each mask can be rated based on comfort. All prototypes will then be collected from the reviewers and destroyed. While this was determined to be the best way to test masks for comfort, the small sample size of people given a mask limits the study. While this is outside of the scope of the class due to time constraints and safety constraints applied by the COVID-19 pandemic, it is recommended that masks be distributed to regular people in low resource settings along with the survey for the best results.

Appendix C

Engineering Standards

This project did not use any specific engineering standards. The nature of the team’s project, creating and developing a DIY mask, is one that uses simpler methods intentionally avoiding an overarching tolerance process. This is done because the final product is one meant to be created by end users in their own homes, where access to and knowledge of various engineering standards will be limited. Some general oversight was provided for certain aspects of the project, however. During the creation of the survey sent out, a representative from the SRC provided valuable input to alter some survey questions to fit the desired goal more effectively. The efficiency testing benefited in a similar manner, since the use of Professor Gamba’s testing rig was run mostly by himself while he worked with the team. The data collected and received by the team was formatted properly and Professor Gamba helped explain how it could be read for analysis in this report.

Engineering Inclusivity

Throughout the course of this project, there were many social identities that the team was conscious of. Even though all social identities were considered as important throughout the project, the ones that were taken into account the most were socioeconomic status, national origin, age, and gender. These were the most important because they impacted how the team saw the users and stakeholders and thus impacted the design as well. The team first had to understand the social power that was had over some of their users. This project was focused around low resource settings, and thus focused on the design being low cost. In order to make sure that the team handled this in the best way possible for the user, 'invited decision making spaces' were used. The team reached out to contacts and possible users in Ghana and asked them what they would normally pay for a mask and the price of some common materials like cotton, silk, nylon, and wire (Ama, 2020; KNUST Team, 2020). When designing the mask, it was important that many different face shapes and sizes be taken into consideration, as the team wanted the mask to fit as many people as possible. Furthermore, the users could be of any national origin and thus speak any language. This is why it was important to depict pictures in the instructions for making the mask. Using pictures and simple language also helps with other invisible identities such as a learning or mental disability. The team could've done a better job with inclusivity by reaching out to other potential users in low resource areas and by conducting the comfort test with those users. This type of testing is recommended for future projects.

Environmental Context Assessment

The first necessary condition for sustainable technologies is whether the system makes significant progress towards an unmet and important environmental or social challenge. The goal of this project is to develop a mask that is both inexpensive, comfortable, uses available resources, and effectively protects wearers from COVID-19. Effectively and inexpensively protecting the general population from COVID-19 is an important social challenge. This project makes significant progress towards this problem, as the proposed DIY mask introduces new features that effectively improve the fit of the mask, the filtration efficiency, and only costs $1.56 USD ($0.34 USD in Ghana) compared to commercial masks which can cost an average of $2.75 per mask. While both the fit of the mask and the filtration efficiency are still in the process of being verified, literature shows that the combination of materials used as a filtration layer in the DIY mask has a filtration efficiency upwards of 94% for particles less than 300 nm in diameter. For reference, common DIY masks made of pure single- or double-layer cotton have a filtration efficiency ranging from 50% to 85% respectively.

The second necessary condition for sustainable technologies is whether there is a potential for the system to lead to undesirable consequences in its lifecycle that overshadow environmental or social benefits. Since the solution is a DIY mask that requires very few materials and is made with low-impact fabrics like cotton, silk, and nylon, there ultimately is not a potential for the system to lead to significant undesirable environmental consequences. The main two environmental considerations lie in the washing phase and the disposal phase of use. In washing the mask, there is a potential for high volumes of water to be used since it needs to be washed between each use. In disposal, none of the materials in the mask can be reused upon reaching the 20 use lifetime of the mask. Therefore, the materials will likely end up in a landfill. While these environmental impacts should not be ignored, they are overshadowed by the significant social benefit of improved protection from COVID-19.

Social Context Assessment

The first thing to look at when evaluating the social impact of a project is to ask whether the system is likely to be adopted and self-sustaining in the market. The project, despite being worthwhile and productive, is unlikely to be adopted and self sustaining in the market. The first and most limiting reason is due to a lack of outreach. The amount of people who will see the instructions for creating the mask will be very low, mostly limited to about 10 people around the project, including Caroline Soyars, Ama, ME 450 Staff, and family. Next, although the instructions and time for creating the mask are relatively brief for a DIY mask, most of the people who receive the instructions will have easier and more convenient alternatives than DIY masks.

Next, one must see if the system is so likely to succeed economically that planetary or social systems would be worse off. The system in question is very unlikely to see widespread adoption, so the scenarios of planetary or social systems being affected negatively is not a concern. If the system were to succeed and become widespread, the lack of manufacturing in the process and the construction of basic materials by hand means a relatively low impact socially.

Finally, one must ask whether the technology is resilient to disruptions in business as usual. The system is a temporary one in nature, due to a fluctuating demand for the need of masks in the long term. Therefore, the system is not very resilient to disruptions in business as usual. When the need to wear masks fades, the system will also become mostly unnecessary.

Ethical Decision Making

Throughout the project, the team considered many ethical factors and dilemmas in the design process and selection of the final design solution. The Michigan Engineering Honor Code and tools discussed in the Ethical Decision Making learning block were used to justify the design decisions made by the team within a context of professional responsibility. The Utilitarianism Test, Universality Test, and Publicity Test were all used to ensure that the project's final design solution of a DIY mask was ethical in nature, holding paramount the safety and health of the general public. When coming up with the project's requirements, the team contacted specialists and researched literature to make sure that the team fully understood the problem being asked and the possible solutions available. The team continued researching literature and interviewing specialists throughout the entire design process in accordance with the fundamental canon of performing services only in which the team is competent in. The Cost-Benefit Test and Reversibility Test were used to determine usable materials for the mask in low resource settings. During prototype testing, the team made sure that all prototypes used were properly disposed of after testing to make sure there was no continued use of the mask after. Since the mask was incomplete at the time, there was a potential that it could prove defective after future use. After receiving the results from filtration efficiency testing, the team realized that the results differed significantly from those posted in literature which performed similar experiments. Instead of hiding this fact through deceptive acts, the team agreed that more testing would be required to verify these results and that this discrepancy should be explained to stakeholders.