Final Report

Transmission Protection at COVID-19 Testing Sites in Ghana

ME 450 - 005 | Fall 2020

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December 8th, 2020

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EXECUTIVE SUMMARY

In Ghana COVID-19 cases have been surging due to community spread. This is the result of overcrowded, low-income neighborhoods with limited access to health services, soap, water, and proper sanitation. Ghana has established 'pop-up' COVID 19 testing sites, but these sites are quite scarce due to a lack of resources. The lack of testing sites creates a risk of transmission from individuals traveling to hospitals and from the concentration of large crowds in the few testing sites available. Furthermore, there is a shortage of personal protective equipment (PPE) for health care workers in Ghana. This shortage requires practices that minimize the use of disposable PPE in order to save supplies for in-patient facilities. This problem is not only specific to Ghana, but is applicable to many countries worldwide. Based on this information, the team identified a need for a low-cost and rapidly deployable interface between patients and healthcare workers that will minimize the use of disposable PPE and allow for safe patient sample collection in low-resource community settings.

The team has developed a set of requirements and specifications that were shaped by information gathered from meetings with stakeholders, professors, sponsors, and research. These requirements and specifications have been refined throughout the design process. The design consists of 16 requirements and 34 specifications addressing usability, safety, cost, functionality, durability/stability, and effectiveness of the device. At this point, because of manufacturing limitations due to COVID-19, the team was unable to create a fully-equipped prototype and was only able to fully verify that four requirements were met through design intent and material choice; those requirements were hand protection, low cost, temperature reading capability, and dimension limits of the booth. The remaining 12 requirements require a physical prototype to be fully verified. Therefore, in lieu of physical verification tests, we have developed a series of verification plans that will allow us to determine if our device fulfills all of its requirements.

After numerous design changes, the team decided upon a testing booth design solution that incorporates gloves attached to the front panel and a table on the outside of the booth. This allows the thermometer, vials, and sample storage to be placed outside of the booth instead of the inside, as was originally designed. The team chose this design to further limit viral transmission between the inside and outside of the booth. The team does take into account that the components on the outside of the booth will be exposed. To address this the team developed a protocol that requires the sanitation of every component after each use. Engineering analyses including tipping/slipping analyses, thermal analysis, and airflow analysis were conducted to test out the design and materials used for the booth. However, these analyses were not as useful for completely verifying requirements because of the assumptions required to perform the theoretical modeling. Strengths of the design would be its low cost and minimal need for machining, while weaknesses would include the conflicting design intentions of added viral particle protection in comparison to minimal booth weight. The team hopes for this project to be continued next semester and to eventually construct a physical model to test and verify all requirements.

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PROBLEM DEFINITION

Problem Overview

In Ghana COVID-19 cases have been surging due to community spread [1]. Many low-income neighborhoods do not have easy access to hospital testing facilities so community testing sites are needed. In areas with high community spread of COVID-19 specifically, safe and efficient COVID-19 testing is essential to reducing the spread of the virus. Testing allows for contact tracing, which is an effective tool for preventing the transmission of the disease. An increase in testing is needed so that anyone who has tested positive can quarantine themselves.

There has been a development of drive-up testing sites at easily accessible locations, such as schools, around the world; however in Ghana these pop-up testing sites are mostly only on hospital grounds[2]. This creates a risk of transmission while traveling to the hospital and also limits testing access. Furthermore, there is a shortage of personal protective equipment (PPE) for health care workers in Ghana [3],[4]. This shortage requires practices that minimize the use of disposable PPE in order to save supplies for in-patient facilities. Additionally, healthcare workers risk self contamination when removing PPE.

Therefore, there is a need for a low-cost and rapidly deployable interface between patients and healthcare workers that will minimize the use of disposable PPE and allow for safe patient sample collection in low-resource community settings.

COVID-19 Background

In order to efficiently and effectively address the problem, some research was first done on COVID-19 or coronavirus disease 19 [5]. COVID-19 is an illness caused by a new coronavirus that has spread throughout the world. The symptoms of COVID-19 can range from the carrier having no symptoms, mild symptoms, or severe illness that could eventually require the use of a facilitated breathing apparatus (ventilator) or lead to death .

The most common way COVID-19 is spread is by the respiratory droplets of a person who is a carrier of the virus [6]. This can happen when someone comes in close contact, which is defined as six feet or less, with the said carrier. While in close contact, if the carrier happens to sneeze, cough, or simply talk, they release respiratory droplets that can cause infection. One can also become infected by touching a surface or object with the virus on it and then touching their mouth, eyes, or nose.

COVID-19 viral particles are encapsulated in mucus, saliva, or water which can be defined as aerosols or droplets[7]. The CDC classifies aerosols as particles less than 5 μm and classifies droplets as particles that are greater than 5 μm. The coronavirus is viable in aerosols for up to 3 hours. Additionally, the virus, in droplets, can remain the longest on glass for up to 84 hours, 72

hours on plastic, and 4 hours on stainless steel[8]. It was also found that the coronavirus itself is about 0.06 to 0.14 micrometers[7].

Preventing the spread of this infection is very serious because there is currently no publicly available vaccine, although some are currently in production, to protect people against COVID-19 [5]. Additionally, it has been recommended that people stay at home as much as possible, get deliveries and takeout, and complete activities online when possible in order to limit in-person contact as much as possible. When one is in a public setting, it is required that they wear a mask that covers the mouth and nose to protect them as well as others. It is also important that people wash their hands often with antibacterial soap for twenty seconds or more. When washing hands is not an option, an alcohol-based hand sanitizer that contains at least 60% alcohol can be used as a substitute [5].

Everyone is at risk of being infected with COVID-19, so it is important that people take these precautions. People of older age and those who have other serious underlying medical conditions are at a higher risk for a more severe illness outcome from the coronavirus [5].

COVID-19 in Ghanaian Communities

After gaining more knowledge on COVID-19, it was important to understand how this was affecting the communities in Ghana. The research on Ghana showed that as of September 12th of 2020, which is when we began this project, there were a total of 45,655 reported cases of the virus including 294 deaths [1]. A visual representation of where the cases were reported can be seen below in Figure 1. Out of these cases, a total of 23,117 were in Accra, Ghana, which is circled in blue on the map below (Figure 1). Accra is the capital city of Ghana and while there are wealthy individuals there, a majority of the residents live in low-income, densely populated communities that have inadequate infrastructure and services [1]. Additionally, some of these communities have little information regarding COVID-19 and have to travel outside of the area for good healthcare and services.

It is important that the healthcare interface be cost-efficient because it would be in low-income settings where the funding would be considered low/limited [9]. If the personnel are not able to maintain the interface, it won't be used, causing it to be ineffective.

In Ghana there has been a Level 4 warning put out by the CDC that warns people to avoid non-essential travel; other precautions have also been put into place [5]. This restriction has disrupted Ghanaians' access to outside healthcare and services, thus exaggerating the need for a low-cost interface for low-resource communities.

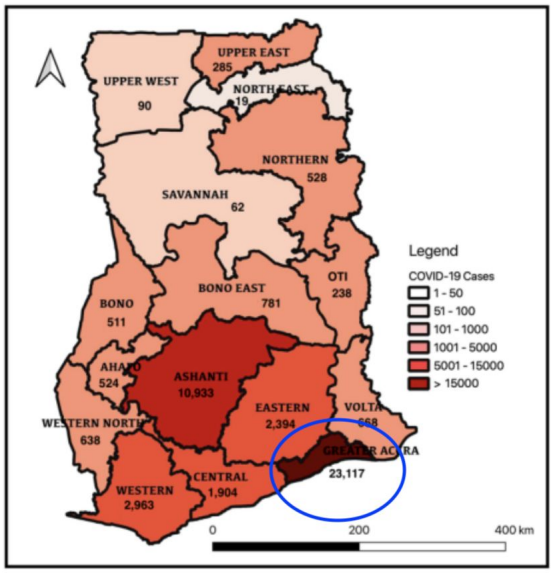


Figure 1: Regional distribution of cumulative COVID-19 cases in Ghana, March - September 2020 [1].

Additionally, as of November 8th, there were reportedly 52,274 cases in Ghana which is an increase of 6,619 from the cases reported in September [1]. There have been a total of 325 deaths from the virus as well. From further analyzing, it became apparent that the majority, or ~3,000, of these new cases came from Accra, Ghana. Recently, the West African Centre for Cell Biology of Infectious Pathogens (WACCBIP) conducted a study that proved that more than one million people living within Accra have been exposed to COVID-19[10]. The study showed that the exposure rate was higher among the people in low-income neighborhoods that tested at places like markets and lory stations than those who tested at higher-end facilities like malls. This study proves that there are indeed inadequate testing facilities in low-income neighborhoods and increases the need for our project. If an affordable testing solution is provided, then Ghana will potentially see a decrease in the spread of virus, specifically within its low-income regions.

Benchmarking Analysis

After researching the problem background and narrowing down our problem statement, our team then explored some existing solutions currently available on the market. From initial information gathering, five major existing products were found and are shown below. These solutions range from being locally produced and used in the United States, designed and implemented by international companies, or manufactured specifically for global distribution and use.

Figure 2: Benchmarked Solutions

A benchmarking table was also created to compare these technologies. To determine the factors of comparison for the existing solutions, findings from initial research and characteristics seen in common across all solutions were considered (such as methods of protection, intended location of use, testing capabilities, etc). Factors considered important to low resource settings were also included (ease of local manufacturing, transferability, ease of training and use).

Commonly in low resource settings, facilities contain obsolete or dysfunctional medical devices. In other cases, expensive equipment may also lie dormant or unused because of the lack of skills and materials for its use, repair or maintenance available [16]. Hence, it is recommended that design considerations for these settings take into account the local context and culture [16]. Our team also made use of holistic contextual factors described in a literature review conducted by Clara Aranda-Jan in the International Journal of Design to evaluate how suitable our five benchmarks would be for low-resource settings [17]. As criteria for our benchmarking table, we considered manufacturing and industrial factors, economic factors, and public health factors. We considered the following questions: Could this benchmark be adequately supplied and produced in Ghana? Is cost reasonable for the design in a low-resource setting? Is there adequate sanitation possible with use of this technology? Is it reusable/plentiful? These criteria were outlined and compared for all benchmarks to evaluate if these products could be considered suitable for low-resource settings and resource-constrained design. The final Benchmarking Table criteria are shown in Figure 3.

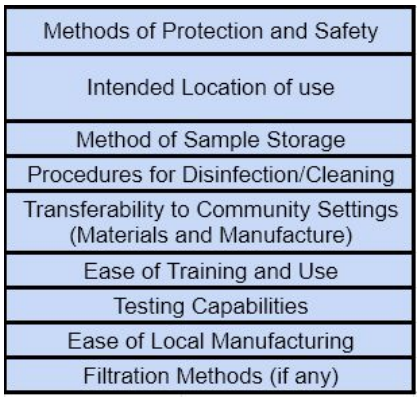


Figure 3: Benchmark Criteria

The full Benchmarking Table is located in Appendix A. During comparison, our team also defined high and low resource settings and used these definitions to categorize benchmarks. *High resource settings* are defined as those that have advanced medical care and resources available, such as the health care system in the United States. *Low resource settings* are defined as locations with less developed infrastructure and professional personnel available, with limited technology access [17]. Both settings can still have shortages of PPE during COVID, but the technology in place in high-resource health care systems is still advanced.

The Ansys Fluent Filtered Testing Booth, K-Walkthrough Sputum Collection Booth, and Eleven COVID Hexapod have been categorized as technologies suited for high-resource settings [11],[13],[14]. These solutions specifically incorporate more high-end or expensive features that add to their overall cost, maintenance, and setup requirements. Examples of this include built-in negative pressure filtration systems, airtight sealed booths, exhaust systems with HEPA filtration and external power, and even UV-C light based disinfection methods, which is a feature present in the K-Walkthrough Booth. Based on this, these technologies were seen as unsuitable for widespread or long-term use in a country like Ghana, where such technology may not be readily available or sustainable.

The Testing Booth by ROOM and Jacomex Testing Cabin have been categorized as technologies suitable for all resource settings, which includes low, middle, and high resource settings [12],[15]. These models were judged as suitable for a range of different locations based on a few common features: operation with no electricity/power, collapsible or compact designs, open source information for manufacture, and no built-in disinfection methods.

In terms of solution gaps present in the models we researched, most primarily focus on providing a barrier or filtration between care providers and other individuals for collecting spit or sputum samples, whereas testing or sample storage is achieved by other methods/devices not included with a testing booth. Additionally, these models often do not have methods/accomodations in

place for measuring patient temperature, as this is a common way to screen individuals for COVID-19. However, some solutions have characteristics that support easy transferability to low resource settings, delivery, and setup. Rapid deployment can be achieved by collapsible designs and compact shapes. However, we can also utilize some of the characteristics that make technologies suited for low resource settings. It should also be noted that many of the current testing solutions developed around the world are quite expensive. The price range we found for current benchmarks, such as the Room and K-Walkthrough booths shown below, went from $750-$2,500, with many of the lower price models requiring a large amount of personal protective equipment [11], [12],[13],[14]. As we stated earlier, Ghana is experiencing a PPE shortage, which means that a novel solution to this problem is required.

Requirements And Specifications

Table 1 below summarizes the requirements and specifications created for the problem statement. The table has been organized according to priority. Each of the requirements has been given a priority value from 1-3 based on feedback from the stakeholders. A priority of 1 indicates that the requirement is mandatory for the device to act as a solution to our problem. A priority of 3 means that that requirement would be beneficial but is not necessary for the device to fulfil its function.

Table 1: Requirements and Specifications List

Priority	Requirements	Specifications
1	Viral Particle Protection Between Users and Caregivers[18],[19]	- Full device has the capability to filter 95-100% of particles ≥ 0.3 um
1	Hand Protection for Caregivers[11],[13],[12],[20],[21].[19],[22]	-Cuff length and protection covers >= 50% of the user's forearm -Pass Purdue Pegboard Dexterity Test -Material used for hand protection can be disinfected with 10-13% diluted bleach solution 50+ times without deterioration -0% direct physical skin-to-skin contact between patients and caregivers -Quality compliant with standards: EU standard directive 93/42/EEC Class I, EN 455, EU standard directive 89/686/EEC Category III,

		EN 374, ANSI/ISEA 105-2011, ASTM D6319-10 or equivalent
1	Isolated & Clear Vocal Communication Between Patients and Caregivers[4],[23], [24]	-Device allows for vocal clarity and isolation within a 1 meter distance in the range of 40-80 dB (based on 60 dB as the average noise level of human voices and conversation) -Interfaces will have a soundproof rating of STC-35 (loud speech is audible but not intelligible) to isolate patient-caregiver conversations
1	Sample Storage [25],[26],[27],[28]	-Samples may be stored in refrigeration at 2 - 8^{o}C for 72 hours -Can accommodate up to 1000 isolated samples at a given time
1	Durability[4],[15]	-20 deployments over 6 months -Lasts ≥ 6 months with frequent daily use
1	Stability[29],[30]	-Able to withstand 100 N of force generated by user interaction in any direction without parts dislodging or tipping -Able to withstand wind speed of 1-13.5 m/s [Light air to a strong breeze] from any direction without parts dislodging or tipping
1	Airflow [31],[32], [33]	-0.35 air changes per hour but not less than 15 cubic feet of air per minute (cfm) per person -Temperature should be maintained at 27-30^{o}C
1	Low Cost[4],[13]	-Device costs ≤ $853.00 to make
~~1~~	~~Power Utilization[33],[34],[3]~~	~~1-2 kWh for ≥ 6 months.~~ ~~-Can be powered via battery or power outlet via Ghanain standard voltage of 230 V and 50 Hz frequency~~

2	User-friendly Operation[4],[11],[36]	- ≤ 2 days of training required to learn how to operate/use the device -Zero written commands are required for patient use of the device
2	Environmental Protection[37],[38]	-Compliant with IP55 standard (EN 60529) -Device offers protection from total dust ingress and particles of 0.1- 1 mm size -Protection against low-pressure jets (6.3 mm) of directed water from any angle (limited ingress permitted with no harmful effects)
2	Temperature Reading Capability[39],[40]	-Uncertainty of ±0.5°C over the temperature range of at least 34-39°C -Stability and drift are less than 0.2°C within a timeframe - Non-contact based determination of temperature
2	Rapid Distribution and Deployment[4],[13]	-≤ 1 hour for set up - Device can be stored at at 1.5m by 1m by 0.5m -Device can be set up by 1 person
2	Dimensions[11],[41]	-2.1 m (H) x 1 m (W) x 0.75 m (L) -Device can accommodate patients of 1.496 m height to 1.859 m height (Ghanain population of 5th percentile female to 95th percentile male as per a 2015 study with n= 261) -Device can accommodate 2x the width of the 95th percentile male's hip width distance of 0.418 m

		(Shoulder or max width dimensions not available)
3	Material Acquisition[4]	-100% of materials that produce the final device are available in Ghana
3	Location of Manufacture[4]	-100% of the manufacturing steps, including final assembly, can be performed in Ghana
3	Non-intimidating Appearance[42],[43]	-Achieves a score of at least 4 on a 5-point Likert scale that quantifies level of anxiety with medical device appearance

The requirements and specifications outlined in the table above are explored in more detail below. It should also be noted that two requirements were removed since DR1, specifically "Sample Transfer" and "Sample Testing." The specifications for the "Sample Transfer" requirement were folded into the specifications for hand protection as the main purpose of the requirement was that there would be no direct physical skin-to-skin contact between caregivers and patients. The "Sample Testing" requirement was also removed after speaking with one of our sponsors, Mr. George Boadu. Initially, the device allowed for samples to be tested on site. However, during the interview with Mr. George Boadu, he stated that the PCR tests currently used are too sensitive, slow, and expensive to be used commonly in the device. Therefore, until a smaller, faster, more robust testing methodology is approved, the device will focus on sample collection alone

Viral Particle Protection Between Users and Caregivers:
The device should be able to provide caregivers with proper respiratory protection from viral particles. The specification was generated by using the specifications list for COVID-19 PPE provided by the Ghanaian government[18]. The list mandated that all healthcare workers use N95 masks, as a minimum standard of protection. Given that N95 masks are certified to filter at least 95% of particles ≥ 0.3 μm, the device must be able to provide caregivers with at least the same amount of protection[18].

Hand Protection for Caregivers:
The device must be able to prevent any direct physical skin-to-skin contact between patients and caregivers. This is based on relevant benchmarking standards as well as standards used by the federal government and CDC[11],[12],[13],[20],[22]. Given that one of the main purposes of the device is to minimize the use of disposable PPE, the material used for hand protection must also be able to be sanitized after interactions with potentially contagious patients. Based on recommendations on disinfection by the CDC, the material should be able to withstand disinfection with 10-13%

diluted bleach solution at least 50 times without degradation[22]. Based on the specifications list for COVID-19 PPE provided by the Ghanaian government, the hand protection should cover at least 50% of the user's forearm and should be compliant with the EU standard directives stated in the specification section[19]. The hand protection also must not inhibit the dexterity/performance of the users. Therefore, it must pass the Purdue Pegboard Dexterity Test, which is designed to ensure that a user's dexterity is not significantly impacted by a given form of hand protection[21].

Isolated & Clear Vocal Communication Between Patients and Caregivers:
Based on stakeholder interviews, it became clear that since literacy was an issue within Ghana, any communication between patients and caregivers should be vocal[3]. Using standards for appropriate vocal clarity the device should allow patients to communicate with caregivers at noise levels between 40-80 dB, given that 60 dB is the average noise level of a human conversation[23]. This noise level should be conducted within 1 meter of distance as this is the expected distance between patients and caregivers during interaction[23]. The issue of privacy was also raised by our stakeholders. Given that patients shouldn't be able to overhear each other's conversations, an additional specification was added to ensure privacy. Using industry standards for soundproofing and confidential communication, the interfaces between patients for our device should have a sound proof rating of STC-35, where loud speech is audible but not intelligible[24].

Sample Storage:
The project stakeholders informed us that Ghana primarily used saliva samples to test for COVID-19[3]. Based on recommendations from the CDC for storing saliva samples, the device should be able to store samples at 2-8°C for 72 hours in order to ensure the virus can still be detected[25],[26]. The number of samples the device should be able to store is also important. The number of samples needed will depend on the population of the city where the device is deployed. We can use the city of Accra, Ghana as an example. Accra has a population of ~2.5 million people[27]. Based on the testing rate in cities in the United States that have similar population sizes (Houston, Texas or Chicago, Illinois), we should expect to use ~1,000 tests per day[28]. However, it should be noted that the actual number of tests required is dependent on our stakeholders' needs. As such, we have reached out to them and are currently awaiting further feedback.

Durability:
The device must be able to withstand at least 20 different deployments. This value was generated after looking at the deployment rates for relevant benchmarks[12],[15]. Based on feedback from our stakeholders, the device must also be able to last at least 6 months with frequent daily use[3]. This value is based on the amount of time that the device will be in circulation before being removed.

Stability:
The device must also be stable enough that it can withstand perturbations from wind or human interaction. Using the standards developed for the average speed of wind, the device must be able to withstand wind speeds of at least 1-13.5 m/s without any parts being dislodged[21],[30]. Given that human interactions can also destabilize the device through people stumbling or leaning on the device, a specification was also added to prevent this. A discussion was held with our stakeholders on the amount of force that the device should be able to withstand while still remaining cost-efficient. Therefore, the device must be able to withstand at least 100 N of force generated from user interaction in any direction without any parts dislodging[3].

Airflow:
Based on DR1 feedback from our stakeholders, the device must provide sufficient airflow to allow caregivers to breathe easily. Based on industry standards for enclosed airflow, the device must provide 0.35 air changes per hour, while also allowing for at least 15 ft^3 of air per minute per person[31], [32]. The point was also raised that the temperature within the device needed to be maintained at comfortable levels. Using the average temperature for Ghanaian summers, the airflow in the device should also maintain a temperature range of 27-30°C [33].

Low Cost:
Initially, the cost generated in this list was based on benchmarking standards and, as a result, the price of the device was set at $250.00[12], [15]. However, based on interviews with the project sponsors, the maximum cost for producing the device was updated from $250 to $853 [3]. This value was based on the amount of money used in the previous COVID-19 testing projects performed in Ghana[3].

User-friendly Operation:
Based on interviews with the project stakeholders, the device must be approachable to both patients and caregivers. Given the literacy rates in Ghana, the stakeholders stated that the device should not require any of the patients to read/write[3], [36]. With regards to the caregivers, they should be able to learn how to operate the device within 2 days. The standards for proficiency and training length were determined using similar concept benchmarks. At the end of the training period caregivers should be able to collect samples at a rate of 1 patient per 8 minutes[11].

Environmental Protection:
The device must be properly protected from the environment in order to prevent sample contamination and to protect the caregivers from inclement weather. Given that Ghana has a rainy season, the interior of the device must be sheltered from rain. In order to prevent sample contamination and to keep the device interior clean, the device should also prevent the entry of dust and dirt particles. These 2 conditions can be combined using the standards employed while producing electronic devices. Therefore, the device should be compliant with the IP55 rating

using the EN 60529 standard[37]. This means that the device would provide protection from dust particles of 0.1-1 mm in size and would also limit the ingress of low-pressure jets of water from any angle to ensure that there are no harmful effects[38].

Temperature Reading Capability:
Given that body temperature is used as an early screening indicator for COVID-19 infection the device should be able to allow caregivers to take the temperature of patients[39]. The device must be able to read temperatures within the human body temperature range of 34-39°C[40]. Using benchmarking standards outlined by the FDA, the device should also have a maximum uncertainty of ±0.5°C and keep drift down to less than 0.2°C[40]. Given that non-contact thermometers are currently being used in Ghana to take temperatures, the device will also employ non-contact thermometers[3].

Rapid Distribution and Deployment:
Based on conversations with the project stakeholders as well as benchmarking standards, the distribution and deployment requirement was modified to have the device set up in 1 hour and to allow the device to be compacted into 1.5 x 1 x 0.5 meters for travel[3],[13]. Mr. George Boadu mentioned that rural areas have very few healthcare professionals available. With this in mind, the device should be able to be set-up by 1 person[3]. However, the exact number of people involved in the set-up is still uncertain as it will depend on the number of people available for testing efforts. We have reached out to Mr. Boadu to confirm how many people will be available for set-up.

Dimensions:
The dimensions provided in the table above are initial values that are subject to change. At a minimum the device should be able to accommodate a wide range of heights in the Ghanain population[11]. This was specified by using the 95th percentile male height and 5th percentile female height as our upper and lower limits respectively. The device should also have a minimum width that accommodates more than 2x the width of its users' hips to allow for easy movement[41]. We are still determining what the form of our solution will be (i.e. mobile design vs stationary floor plan). Therefore, the specifications for this requirement are still somewhat flexible.

Material Acquisition:
Based on stakeholder interviews, the materials used to manufacture the device should all be available within Ghana[3].

Location of Manufacturer:
Based on stakeholder interviews, the actual device manufacturing process should take place completely within Ghana[3].

Non-intimidating Appearance:
Based on stakeholders interviews, the device must not be intimidating to patients[3]. The specification for the appearance of the device was changed to utilize a modified 5-point Likert scale for anxiety from medical devices[42]. The scale was used to test the reactions of young children to MRI machines[43]. The device must score at least a 4 out of 5 on the scale, which indicates that the patients are comfortable with the device.

Removal of Power Requirement:
By Design Review 3, our requirement for power storage had been removed (which is shown in a strikethrough format below). This requirement was present because of the need of refrigeration within the final design, which our team assumed would require a solution that required electricity or external power. This meant that at the time of Design Review 1 our requirement for power storage was not solution-neutral. However, after recommendations from Dr. Aubree Gordon, we have found reusable ice compartments known as Credo Cubes that are used for storage of materials at low temperatures for our desired duration (2-8 ºC for 72 hours, as seen in the sample storage requirement and specification). Additionally, we have confirmed these units can be shipped to Ghana and included them within our bill of materials in Appendix B. Because our team has now found and confirmed usage of an alternative, powerless solution for refrigeration, the power utilization specification and requirement has been removed. At this time, cost and shipping is still being finalized for the Credo Cube unit, so the cost is not listed in the current bill of materials.

Requirements & Specifications Finalization:
In order to judge the completeness of our requirements, we used a few of the parameters provided by David Garvin and Donald Firesmith[44]. We focused primarily on our device's performance, conformance, durability, usability, and available features. In order to finalize our requirements and specifications, the list was presented to our primary stakeholders, George Boadu and Dr. Elsie Effah-Kaufmann, for approval.

CONCEPT EXPLORATION

Concept Generation

Our team approached the concept generation stage in two distinct phases. We began with individual brainstorming and then moved on to concept benchmarking. We used this approach in order to generate a large amount of novel ideas to start the development process. The concepts generated during this phase are provided in Figure 4 below.

Individual Brainstorming

We began by using individual brainstorming where each group member generated 4 ideas over the course of 2 days. This resulted in 16 original concepts overall. We decided to use individual brainstorming instead of group brainstorming to prevent the ideas of any one group member from monopolizing the discussion. This technique also allowed all group members to contribute equally and ensured a greater variety of ideas. After each group member generated their concepts, they were compiled into a Google Sheets document. Rough drawings of each concept were also submitted to help group members visualize the concepts.

Concept Benchmarking

Please note that this phase is distinct from the concept benchmarking performed during the background research for our project. In this phase, we selected the top five concepts from the industry benchmarks. Out of all five selected benchmarks, each product was either effective at preventing viral particle exposure (Ansys Booth) or was suited for low-resource settings (Room). However, none of the benchmarks were able to accomplish both goals. Since our device needs to be low-cost and needs to provide protection from viral particles, as well as provide storage space and temperature reading capability, we decided to develop additional concepts that still utilized the best aspects of the top 5 benchmarks. We used design heuristics and SCAMPER analysis to generate modified concepts that addressed these needs and were based on our benchmarks. This is described in the following section.

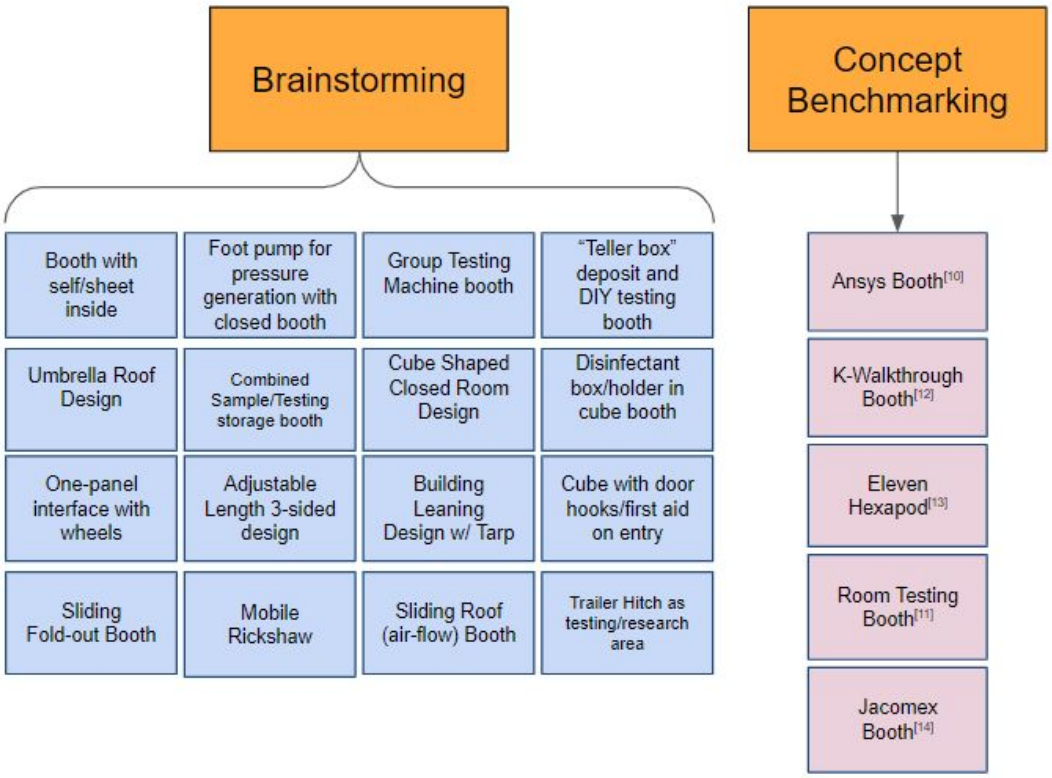


Figure 4: Overview of Concepts from Concept Generation

Concept Development

After creating 21 ideas during concept generation, we used three concept development methods to further explore the solution space. In chronological order the methods used were (1) design heuristics, (2) SCAMPER, and (3) morphological analysis. We decided to end our concept generation and development once we had a wide spread of novel ideas that were favorable to our sponsors. At the end of the concept generation and development, we had 46 different concepts that fell into four main categories of ideas: closed floor designs, open floor designs, mobile designs, and building modifications. The final collection of ideas is presented in Figure 5.

Design Heuristics

Design heuristics involves using existing principles (like using the opposite surface) to modify an existing concept or design. The purpose of the technique is to generate multiple, varied concepts by applying different design heuristics. One of the main reasons that we used design heuristics is that it allows for a more structured approach to concept generation since you have prefabricated design principles that you can base your ideas on. We utilized design heuristics to come up with a large number of concepts that were significantly different from our brainstorming and benchmarking concepts. A list of the design heuristics we used most during the concept development phase, and the concepts they inspired, are provided in Appendix B [45].

SCAMPER

After performing brainstorming and design heuristics, we realized that many of our concepts were suited to fulfilling one aspect of our problem (respiratory protection vs. vocal communication), rather than addressing all of the issues at once. In order to leverage the most beneficial components of our different concepts, we used SCAMPER to modify the parts of our design that could be improved or that were less than ideal. SCAMPER refers to a concept development technique that modifies part(s) of a design to create a new solution. For example, one of our brainstorming concepts was for an enclosed cube design, but during concept development we used the "Eliminate" principle to take away the back wall of the design to increase airflow. As mentioned before, one of the main advantages of SCAMPER was that it allowed us to identify specific parts of our designs to change. However, one of the disadvantages to the technique was that some of the concepts generated seemed to be rather unrealistic. Our team overcame this problem by suspending evaluation of the concepts for the time being and focusing on simply generating a wide array of diverse ideas.

Table 2: SCAMPER Components

SCAMPER[46]	
Substitute	Substituting part of a design with something from

	another concept
Combine	Combining 2 or more parts of the design
Adapt	Adapting parts of the device to change their nature
Magnify, Modify	Adjusting part or the entire product by distorting it in a different way
Put to Other Uses	Utilizing a concept from somewhere else or using the product in another way
Eliminate	Eliminating a part of the device
Rearrange, Reverse	Reordering the process or parts of the device

Morphological Analysis

Morphological analysis is a concept development method that involves breaking down a device into its most rudimentary functional components and then proposing potential solutions for each of the components. We chose this to be our last concept development technique in order to ensure that we were accounting for every part of our device. We worked as a group to generate various ideas which are documented in the chart in Appendix C. We used a Google Sheets document to store our ideas as we worked so that we could see what the other group members were doing. We chose our subfunctions to be the features that our sponsors highlighted as having the highest importance in allowing the device to achieve its purpose of minimizing disposable PPE use while also protecting its caregivers during sample collection. For example, to interact with patients safely, caregivers need proper respiratory protection. To be able to save samples for testing, sample storage is another key element. The benefit of this approach was that it allowed us to look at our device as multiple, separate problems with unique solutions. We were also able to account for each part of our device from the patient-caregiver interface to the sample storage space. However, one of the disadvantages was that solutions that could solve multiple problems at once, such as incorporating the airflow system into the refrigeration, were not as prominent. We were able to overcome this issue by looking over the ideas from the morphological chart and determining which ones could be combined into larger concepts.

As the result of concept generation and development, our team created the following 46 concepts in Figure 5.

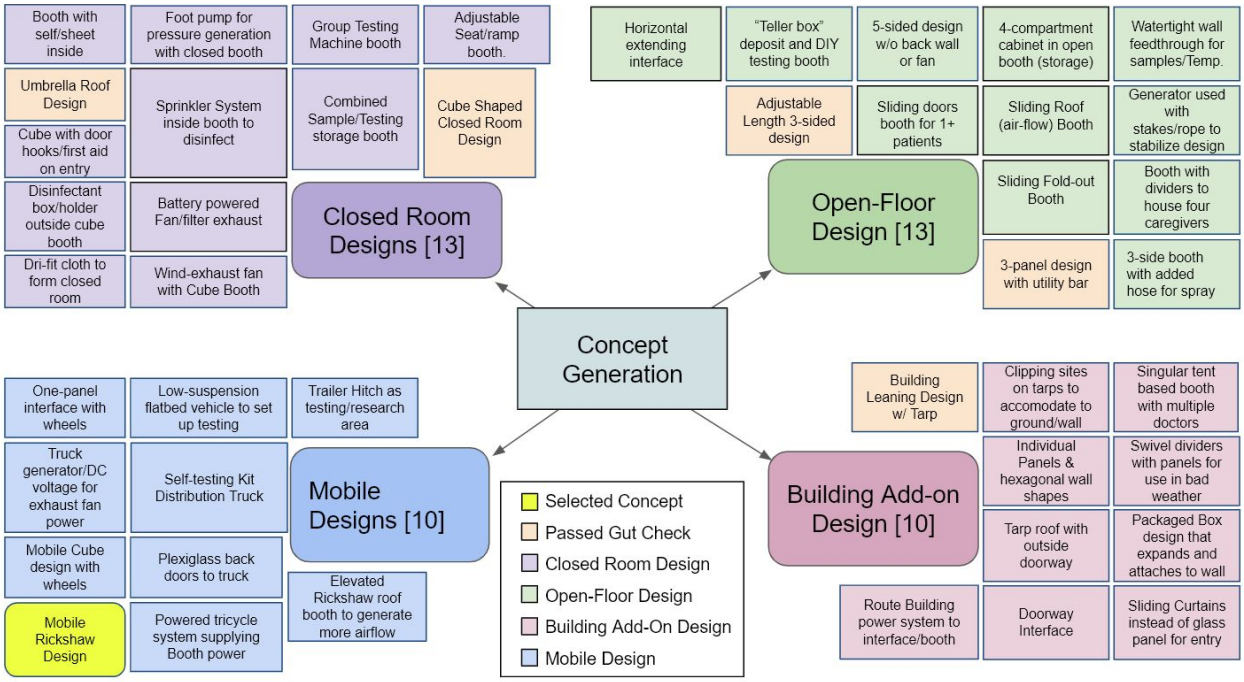


Figure 5: Overview of Non-selected Concepts

Concept Evaluation & Selection

Overview of Concept Evaluation and Selection Process

It should be noted that the concept selected in this section underwent further evolution that changed it from a rickshaw-focused concept into a stand-alone booth for our current design. This will be discussed further in the "Evolution of Concept" section.

After the team generated 46 concepts in total, two methods were used to evaluate the feasibility and features of each concept. First, a higher level gut check, including a discussion of concepts with our stakeholder, was used to narrow our viable concepts from 46 to six. Then, a more in-depth weighted decision matrix was used to ultimately decide upon our top three selected concepts. This order was primarily chosen to ensure that our team could initially fail concepts that were considered unlikely to work based on logic and common sense and instead focus primarily on those that had the potential to work. Afterward, we pursued a more in-depth analysis by evaluating six concepts specifically on how well they adhered to our requirements and specifications using a decision matrix. An overview of this process is shown below in Figure 6.

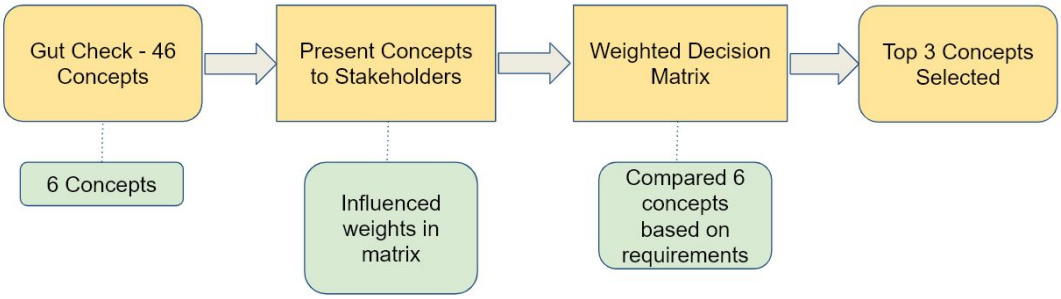


Figure 6: Overview of Concept Evaluation and Selection Process

Gut Check

A gut check involves performing a basic preliminary review of a solution set before using more specific concept screening tools. Our team used specific constraints and barriers as a way to eliminate designs that were seen as unreasonable for low-resource settings. This was based on similar criteria and rationale our team used when evaluating the existing solutions within our benchmarking table. Each of our 46 concepts were evaluated based on three primary criteria: technology readiness, power usage, and overall cost and maintenance. These criteria were expressed in the following questions: Could the generated concept be manufactured with common processes or are more custom parts/work required? Could concepts function effectively in rural or isolated environments with little to no power usage? Could the device be produced at a low cost and be sustainable over time? Each concept was chosen to collectively pass or fail based on its fulfillment of these three criteria.

During this stage, our team also openly discussed and reviewed ten of our chosen concepts with a primary stakeholder, Mr. George Boadu from the Ghana Society of Biomedical Engineers, to directly assess requirements and feasibility based on his judgment. That allowed us to gauge which concepts were most favorable in that sense as well. This was done because Mr. Boadu has engineering experience and in-person insight about conditions in Ghana and how applicable our concepts may have been. We used his suggestions to highlight specific concepts that could be the most reasonable for low resource settings, and his knowledge was used to bridge the gaps of anything our team may not have considered about Ghanain settings. Lastly, among our 46 concepts, we found that some concepts were rather similar to others with only slight modifications as a result of our concept generation process, so this initial gut check method also allowed us to collectively pass or remove multiple concepts.

The advantages with this method included the ability for our team to eliminate concepts without experimentation or numerical ratings. However, in terms of disadvantages, this process had been more high level and top-down focused, so not as much attention may have been given to alternative concepts or similar concepts/features. The six designs remaining at this stage are shown in Figure 7 below. Additional details regarding these designs can be found in the Appendices and Concept Generation section above.

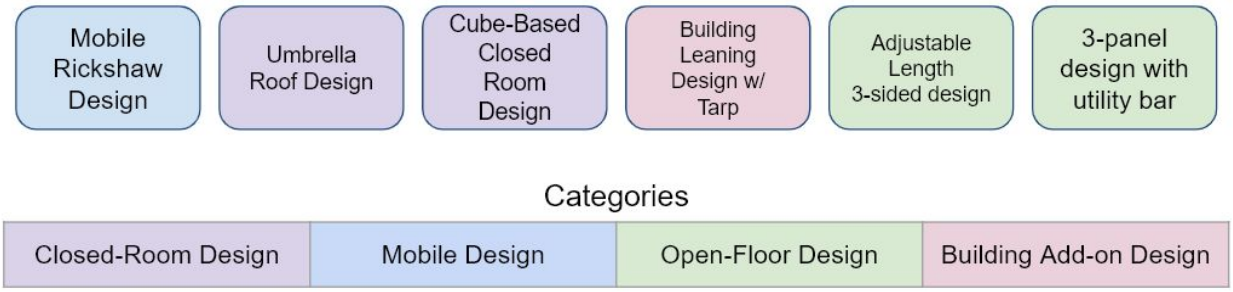


Figure 7: Six Selected Concepts after Gut Check Completion

Weighted Decision Matrix

With a decision matrix, concepts can be evaluated based on how well they adhere to user requirements and specifications. In this case, concepts are not directly compared to one another, but only to the criteria of evaluation during the process. Our team made use of a weighted decision matrix to evaluate our six concepts at a greater depth and with specific regard for requirements and specifications. Our stakeholder requirements could be given varying priorities through weights, and each concept can then be scored on how well that concept satisfied each requirement. The dual weighting method our team made use of has been sourced from Casewestern Reserve University's Biomedical Engineering Department and will be described at length below [47].

Firstly, an objective tree outlining the weights and categories of each requirement was made. For our first weighting, we used the three priorities originally set when developing requirements & specifications and assigned numerical weights to what are designated as *Main Criteria*. A weight of 0.5 was assigned for the greatest priority requirements, a weight of 0.3 was assigned for middle priority requirements, a weight of 0.2 was assigned for low priority requirements. We chose these specific numerical weights for each requirement category to ensure that we did not strongly disregard the lower priority requirements or over-emphasize the higher priority requirements with more extreme weightings.

For our second round of weights, we also discussed individual requirements within each category as a team and chose weight factors based on which requirements were most important to our stakeholders. Durability and stability were combined into one requirement and evaluated together for brevity, and dimensions were redefined to assess potential equipment storage space for each concept. Otherwise, all other requirements were included as outlined in our requirements and specification table.

We used insight from our conversations with Mr. George Boadu and Dr. Elsie Effah-Kaufmann to predictively assign numerical weights and prioritize some requirements over others. In all

instances, the sum of weightings are made equivalent to one. A greater weight means that a higher score in that respective category would factor more into the final score for that concept. Our complete objective tree is shown in Figure 8 below.

Objective Tree

Main Criteria	Weight	Sum	Sub-Criteria	Weight	Sum
Greatest Priority Requirements	0.5	1	Viral Particle Protection	0.35	1
			Hand Protection	0.05	
			Clear Vocal Communication	0.05	
			Durable and Stable	0.1	
			Airflow	0.15	
			Low Cost	0.2	
			Low Power Usage	0.1	
Mid-priority Requirements	0.3		User Friendly Operation	0.05	1
			Environmental Protection	0.4	
			Temp Reading Capability	0.05	
			Rapid Deployment & Distribution	0.2	
			Fits cooling system, windows, testing, people	0.3	
Lower Priority Requirements	0.2		Materials locally sourced	0.15	1
			Can be Manufactured in Ghana	0.3	
			Non-intimidating Appearance [33],[34]	0.5	
			Sample Testing Possible	0.05	

Scoring Scale

0	Totally Useless	6	Good with some drawbacks
1	Very inadequate	7	Good
2	Weak	8	Very Good
3	Poor	9	Excellent (exceeds requirements)
4	Tolerable	10	Ideal
5	Satisfactory		

Figure 8: Respective Weights for Categories and Specific Requirements used in the Weighted Decision Matrix

Next, each of our six concept solutions was rated in these categories based on how well it satisfied each requirement. The scoring scale shown in Figure 8 was used and ranks a device's suitability for a given requirement from 1 to 10, or from Useless to Ideal. To determine a final score for each concept, each concept's score in a particular requirement is multiplied by the Main Criteria weight (based on priority of the requirement category) and also by the weight for the Sub-Criteria (the specific requirement weights themselves). For instance, if a concept scored 8 in the category of viral particle protection, the contribution of that category to the overall score is 8 * 0.35 * 0.5. The product of both weights is defined as the overall *weight factor* (in the example

shown, this would be .175 = 0.35 * 0.5) Total scores for each requirement are then added to calculate a concept score. These are shown below for our six resulting concepts. A breakdown of the scores received and the full weighted decision matrix can be found in Appendix D.

Mobile Rickshaw Testing Concept	Cube Design	Umbrella Design
7.015	6.575	6.425
Leaning Design	Room Design with Added Bar	Modular, 3-sided Design
6.525	6.415	6.555

Figure 9: Final Weighted Decision Matrix Scores for Six Selected Concepts

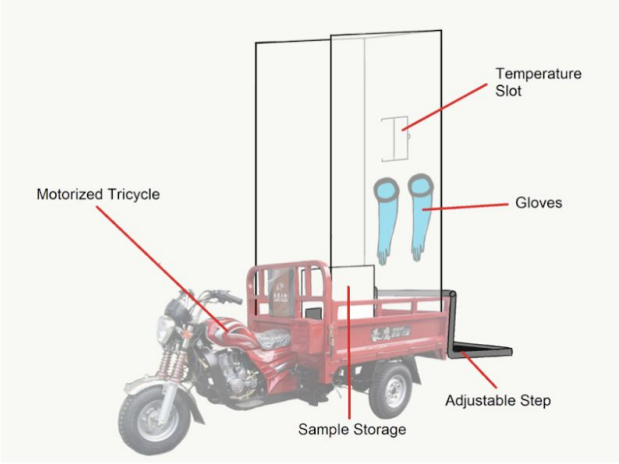
With our results, an incredibly narrow range of scores was seen for our concepts with values from 6-7. This may likely have occurred because positives of one concept and negatives of the same concept may have averaged out the scores. The Mobile Rickshaw design scored the highest and is our currently selected concept, and the cube-based closed room design and Modular Length 3-sided room design scored second and third, respectively. We've chosen the Mobile Rickshaw Design given its favorability and interest from both our stakeholders, Dr. Effah-Kaufman and Mr. Boadu. The advantages and disadvantages of the selected concept will be discussed in greater detail in the following section.

An advantage of this in-depth matrix is that our team could directly assess many of our individual requirements and specifications. In terms of disadvantages, our criteria may have been too expensive or too equally weighted. Along with this, the scores given to each concept are largely subjective based on our limited current knowledge and experience. We may find that some of our judgments could be off after considering design drivers and an engineering analysis. In light of this, we will also keep additional features of our second and third scoring concepts in mind as we move forward, as they did not score much differently from our top concept.

Final Top-Scoring Concept

Concept 1 – Mobile Rickshaw Booth

Below is the Mobile Rickshaw Booth design along with its weighted decision matrix and description.



Design Criterion	Weight Factor	Mobile Rickshaw Concept	
		Score	Rating
Viral Particle Protection	0.175	6	1.05
Hand Protection	0.025	7	0.175
Clear Vocal Communication	0.025	4	0.1
Durable and Stable	0.05	8	0.4
Airflow	0.075	8	0.6
Low Cost	0.1	4	0.4
Low Power Usage	0.05	4	0.2
User Friendly Operation	0.015	7	0.105
Environmental Protection	0.12	9	1.08
Temp Reading Capability	0.015	5	0.075
Rapid Deployment & Distribution	0.06	10	0.6
Fits cooling system, windows,	0.09	5	0.45
Materials locally sourced	0.03	9	0.27
Can be Manufactured in Ghana	0.06	9	0.54
Non-intimidating Appearance	0.1	9	0.9
Sample Testing Possible	0.01	7	0.07
			7.015

Figure 10: Mobile Rickshaw Design (left) with weighted decision matrix (right)

The Mobile Rickshaw Booth concept revolves around using a motorized cargo tricycle that is widely used in Ghana. The concept involves mounting a testing booth on its cargo bay. This is meant to eliminate the need to frequently assemble and disassemble. This feature also allows the device to be mobile and can be transported with ease which is why it had been our most favored concept at the time. The testing booth would be a 3-wall design to allow for an easier entrance into the device that can also be fitted with a tarp roof. The roof would help lower temperatures since the metal cargo bay may cause temperature to increase significantly on sunny days. The testing booth would include the main features from the previous concepts. This includes a temperature slot that can open and close to take the temperature of patients using a non-contact thermometer. The design is also fitted with built in gloves to prevent skin to skin contact between users and patients. This helps with transmission protection. Additionally, the design includes an adjustable step that is meant for shorter patients to step on in order to be at the same level as the testing booth. Lastly, this design might require an additional power source. This concept was selected as the top concept because of its scoring in the weighted decision matrix as well as the positive response it received from our stakeholders, Mr. George Boadu and Dr. Effah-Kaufman.

Advantages of Concept 1

The advantages of this design are that it is rapidly deployable, it is easier to distribute, it is stable, has good airflow, and has its own power source. This design is rapidly deployable due to the fact that the booth would only need to be assembled once and mounted onto the cargo bay of the tricycle. There is no need for users to assemble and disassemble the device over and over again when transporting. Also, this device would be much easier to transport since the device is mobile. Users would be able to drive the device to additional communities that require testing. The vehicle would be able to withstand concrete or dirt roads. This design is also much more stable compared to the other concepts. The booth would be mounted onto the motorcycle with

screws which would keep its position in place. The motorcycle itself is already stable which is an improvement in stability compared to the other devices. Lastly, this design has a power source which may be used to power the appliances inside the booth if the battery meets the power requirements.

Disadvantages of Concept 1

The disadvantages of this design are that viral protection is not the best, vocal communication may be worse than the other concepts, and it is the most expensive design. This design would have limited viral protection as it has openings that expose the inside of the booth to the environment. This may cause rain, dust, and viral particles to get inside the booth. Also, in order to power the appliances of the booth, the vehicle might need to be idling which can make communication between the user and patient difficult. However, this would only matter if the battery of the motorcycle is able to power the appliances inside the booth. Otherwise, an additional power source would be required to power the refrigerator. This leads to the last disadvantage which is that this device is the most expensive. The motorcycle is an expensive component of this device. Prices fluctuate depending if the user is buying a single unit or in bulk.

Second and Third Highest Scoring Concepts:

Concept 2 – Cube-Based Room Design

Below is the Cube-Based Room design along with its description.

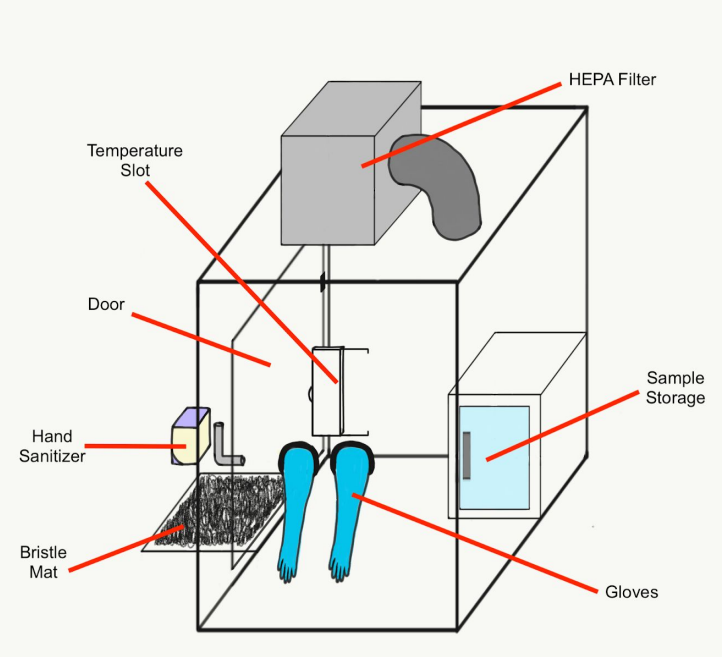


Figure 11: Cube-Based Room Design

The Cube-Based Room Design concept revolves around creating an enclosed testing booth. This design is a 6-wall room to ensure protection from the environment, such as dust, and viral particles. This design includes a filtration system on its roof which comes in the form of a HEPA filter. This design is also fitted with a refrigerated sample storage device to keep samples at adequate temperatures for testing later on. The design is also fitted with a door to provide access to the enclosed room. A hand sanitizer is also fitted into the design to help keep the user's hand protected from the virus. The design is also fitted with a bristle mat to help prevent dust from entering the room. The design is also fitted with a temperature slot for users to use a non-contact thermometer on the patient. Additionally, the design is fitted with built-in gloves to conduct testing on the patients with no contact. Lastly, this design would require a power source.

Advantages of Concept 2

The advantage of this design is that it has excellent viral particles and environmental protection. It is an enclosed system that provides the best transmission protection due to its closed walls and HEPA filter. The device completely surrounds the healthcare worker and protects them while conducting tests. The device also provides protection from the elements and can keep out dust and viral particles traveling through the air.

Disadvantages of Concept 2

The disadvantage of this design is that it has poor airflow inside the device, has a longer deployment process, has a high cost due to more materials and HEPA filter, and may be harder for the user and patient to communicate. This design does not have good airflow since it is an enclosed system with no air conditioning. The system helps filter the air, but temperature inside the booth might be unbearable under Ghana's sunny days. The device also has a longer deployment process since it has much more parts and requires constant assembly and disassembly when trying to transport the device to different communities. This device also has higher cost due to higher material cost and the HEPA filter. The cost of assembly and transportation is also a factor regarding its cost. Lastly, the user and patient might have a difficult time trying to communicate due to sound suppression of the user from inside the device.

Concept 3 – Modular 3-Sided Design

Below is the Modular 3-sided design along with its description.

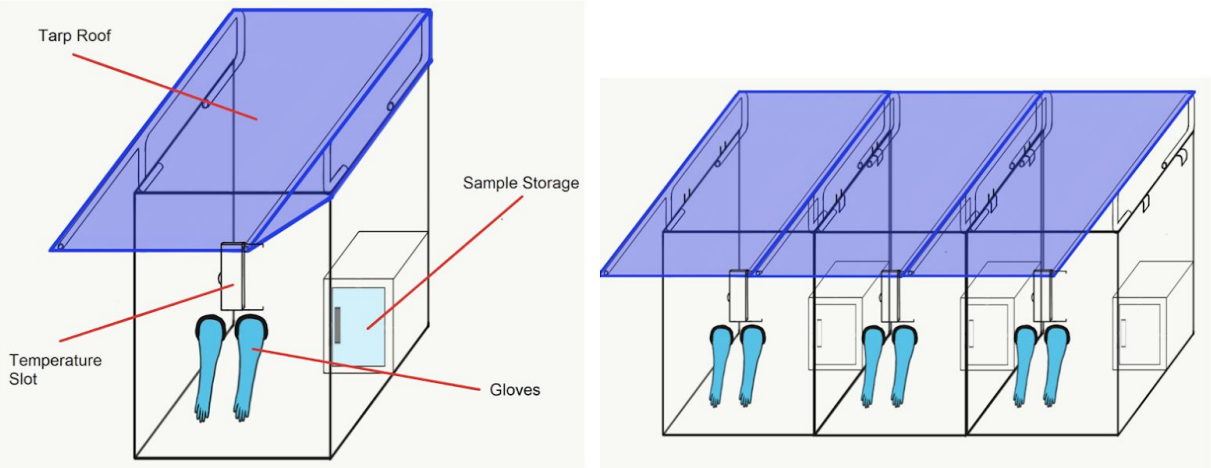


Figure 12: Modular 3-Sided design (left) with stacked design (right)

The Modular 3-Sided Design concept revolves around making the system as simple as possible while making the device stackable for multiple testing sites. This design includes a temperature slot for users to use a non-contact thermometer on the patient. This design is also fitted with built in gloves to prevent the user to have any skin to skin contact with the user. This design only has three walls leaving the base, rear, and roof exposed to the environment. However, this design does include a tarp roof to protect the user and patient from rain or to provide shade, if necessary. Additionally, this design includes hooks on the top of the wall that can be placed on the opposite wall of a different modular booth that has stoppers for the hooks for easy alignment. Assemblers would be able to stack as many as they desire. Lastly, this design would require a power source.

Advantages of Concept 3

The advantages of this design are that airflow is good, vocal communication is much clearer, easier assembly, and costs much less compared to Concept 2. The user and patient would be able to communicate much easier due to the openings of this design. There is less sound suppression due to the openings of the device. The user would also experience much better airflow due to the openings. Air would be able to travel much easier through the device and temperature would not be as bad as concept 1 due to the shade provided by the tarp roof. This concept is also much easier to assemble due to less parts and simpler design. Lastly, the cost of this device is less than concept 1 since it does not have a HEPA filter and consists of less materials.

Disadvantages of Concept 3

The disadvantages of this design are that viral protection is not as good, durability is diminished, stability is poorer compared to Concept 2. This design does not have good viral protection due to the openings that expose the inside of the device to the environment. This affects transmission protection since viral particles may get inside the device. This may also lead to the deterioration

of the device due to the environment. The environment also creates a non-sterile environment within the device. Also, stability is an issue with one modular device since it does not have the rest of the walls to hold the device down with its own weight. This design also required a flat base when staking more booths together. Otherwise, the stacking would not be snug and have gaps in between due to an uneven ground. This may also cause instability with high winds.

Evolution of Selected Concept to Current Design

Over the course of the project, the team had come up with many different versions that were meant to hone in on the requirements that the team's stakeholders had in mind. Many concepts were completely revamped, but the essential features remained constant throughout these variations. These essential features include a slot for the vial, glove holes, and sample storage. The figure below shows the team's timeline of how the selected concept from DR2 changed over the course of a month.

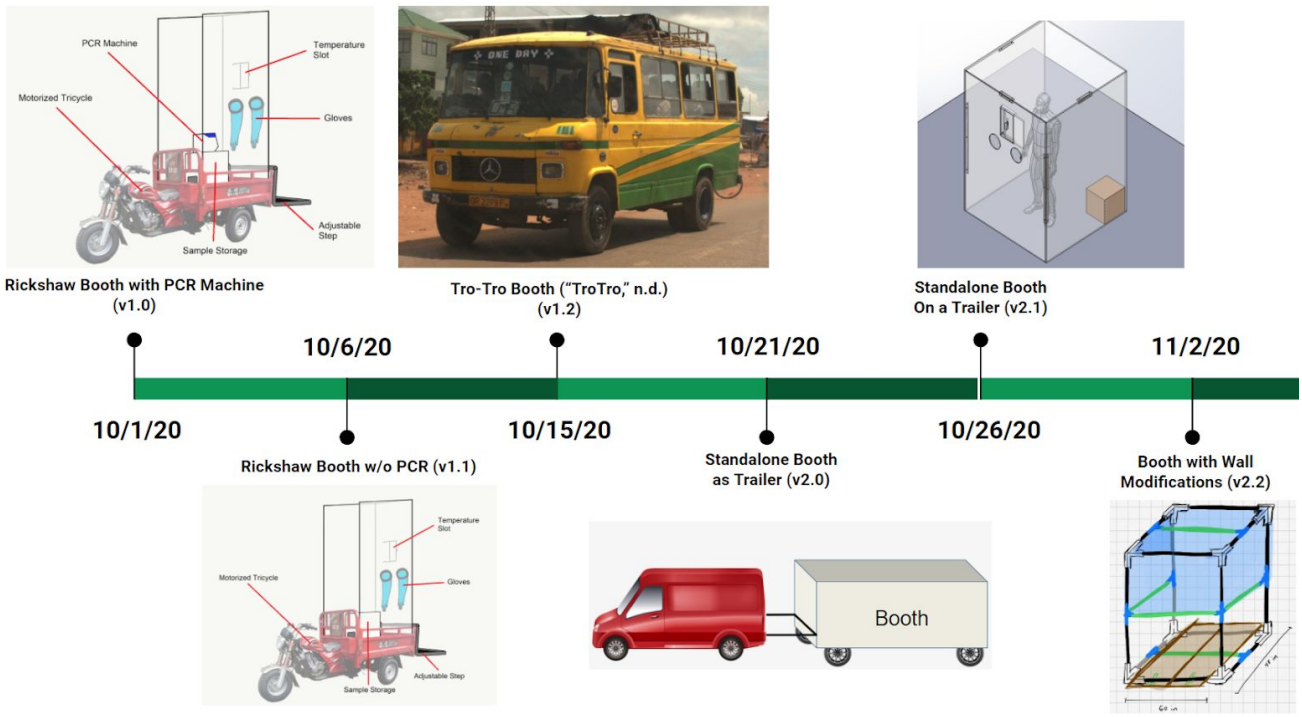


Figure 13: Timeline of the Evolution of Selected Concept

The first selected concept, known as version 1.0, started out as a rickshaw design which incorporated a testing booth on its cargo bay. However, this version had an unnecessary cost of having a PCR machine. At the time, the team's stakeholder stated that a PCR machine was not necessary, but having the capability of storing one was.

This new piece of information changed the design to solely focus on sample collection as shown in version 1.1. However, problems arose due to the small area of the cargo bay, which did not

provide enough space for the healthcare worker to move around in. Additionally, the need to have an elevated platform for patients was also problematic, since there was a possibility that the patient could have fallen. This device also required an additional power source since the motorcycle battery was not enough to power the sample storage.

The next design was to change the vehicle used, as shown in version 1.2. The team decided to experiment with a tro-tro, which may come in the form of a large van or a bus. The idea was to remove the seats from the interior and make a mobile testing unit fitted with sample storage and testing capabilities. This design was a great candidate since the booth would have been mobile and rapidly deployable. However, this design was a much more expensive solution since it required the sourcing of many used or new vehicles. Additionally, finding a way to power the storage device with a car battery was problematic and possibly dangerous if not done correctly.

The team then decided to make the booth mobile by treating it as a utility trailer, as shown in version 2.0, which allowed costs to be reduced. This idea was much more flexible since a majority of vehicles have an associated tow hitch. This means that no specific vehicle would be required for booth transport. Also, the team decided to adopt a portable ice box (the Credo Cube) instead of having a refrigerator. The icebox removed the need of having a power source and cut on costs. However, this design had too many manufacturing needs. Additionally, the booth might have been too heavy to sit upright, since the booth most likely required a metal frame to withstand rough terrain.

The team's next idea was to separate this concept and utilize a utility trailer to transport the booth, as shown in version 2.1. This design incorporates acrylic walls to provide full protection as well as wheels attached to the rear. This design was supposed to mimic a hand trolley that can be pushed up a ramp onto a utility trailer. This also allowed the user to utilize any type of flatbed utility trailer. The dimensions of the booth were adequate with most utility trailers that can be towed by a standard Ghanaian car. However, this design was far too heavy for one person to push. It was also very expensive due to the custom-made acrylic walls.

The team then decided to minimize the use of acrylic walls and create a metallic frame. The design in version 2.2 minimized the use of materials and was lighter. The only problem was the difficulty of manufacturing. The metal frame required the use of welding, which is not convenient for low-cost manufacturing of the booth. Additionally, the use of nuts and bolts might also not be sufficient, and the frame might collapse onto itself when faced with rough terrain during transport. Therefore, using all the information learned throughout this project and the modifications of the team's past designs, the team came up with version 2.3.

Introduction of PVC Model - v2.3

The team had decided to replace the metal frame with PVC tubing. PVC tubing is much lighter, cheaper and durable. This design allowed for a much easier assembly process and was quite adjustable.

This design had a clear wall to view the patient, had arm holes meant for gloves, incorporated the use of a portable ice box, had a sample slot, temperature reading capabilities and surrounded the healthcare worker. The figure below illustrates these key features.

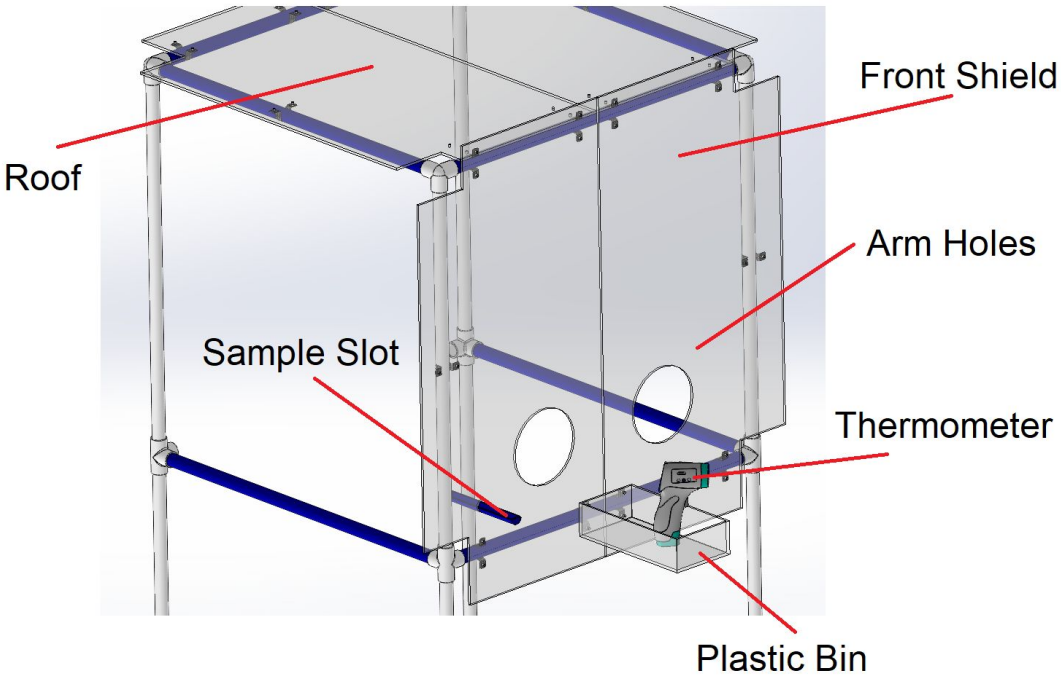


Figure 14: Key Features of Concept - v2.3

This design also minimized the use of acrylic walls by only using two panels. One for the front top half of the device, so the patients and caregivers can see each other while still having a physical barrier between them. Another wall was used for the roof, to protect the user from precipitation such as rain. The rest of the side walls would be covered with an adjustable sun-reflective tarp to protect the worker from viral particles, heat, and precipitation, while saving on costs. The figures below demonstrate what areas of the device are exposed and which will be covered by tarp.

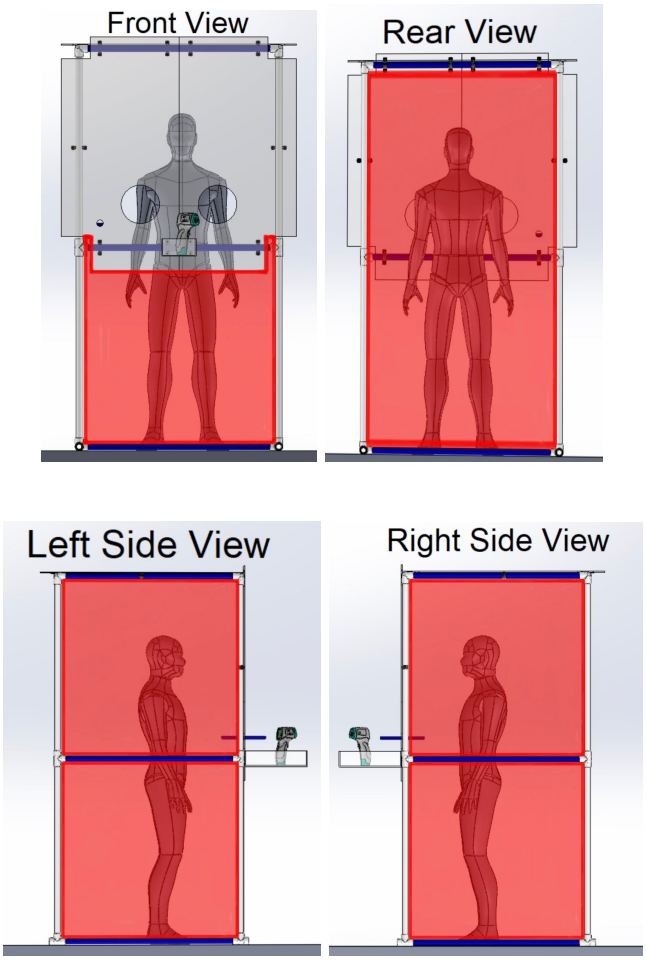


Figure 15: Exposed Sections of Concept - v2.3. The areas shown in red are those not covered by acrylic panels.

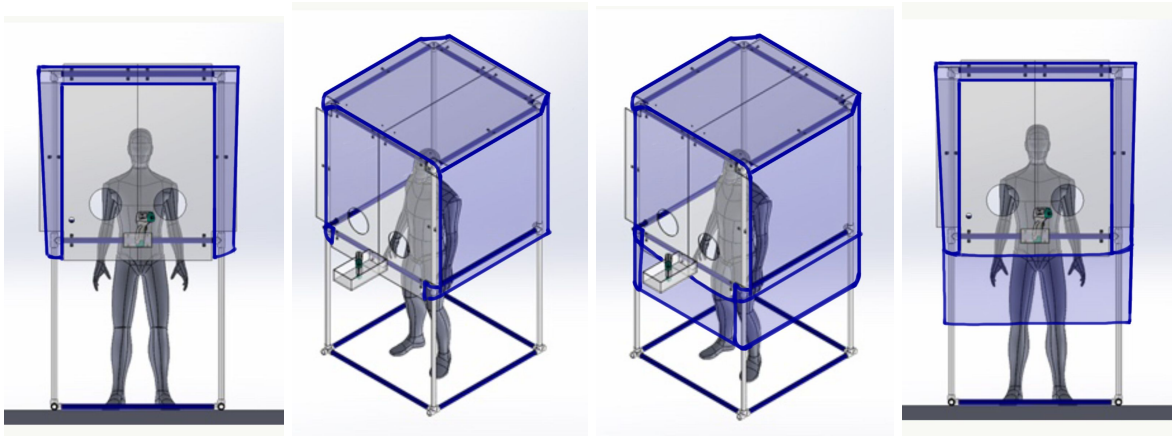


Figure 16: Tarp Covering of Concept - v2.3. The left two images show the tarp in “Position 1” and the right two images show the tarp in “Position 2”.

Moreover, the dimensions of the device were fixed due to the sizing of the PVC tubes. Each segment measures a meter each, which is how the product is sold. The team decided to keep the PVC tubes in their original form to minimize labor work and have a device that is rapidly deployable, which requires a relatively quick assembly. Also, dimensions of the acrylic front panel were adjusted to meet the average dimensions of a Ghanian person. The dimensions of the device are shown in the figures below.

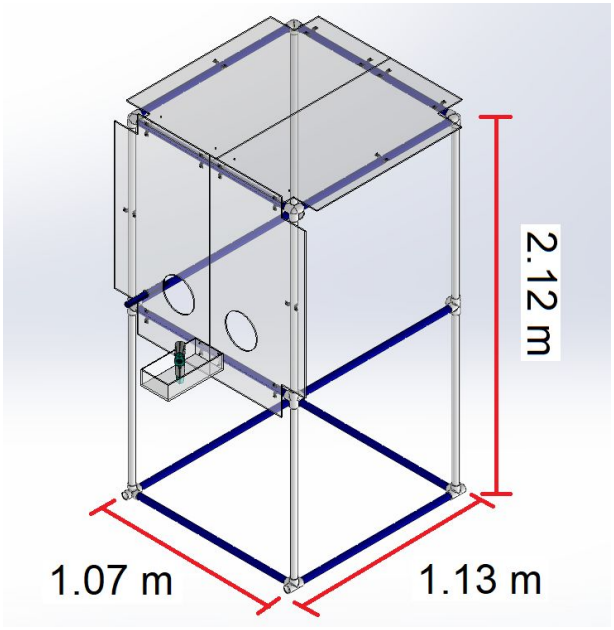


Figure 17: Outer Dimensions of Concept - v2.3

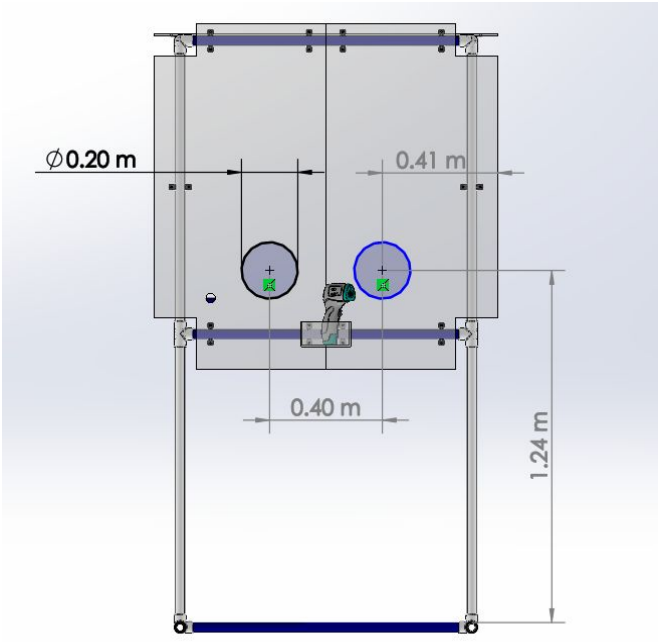


Figure 18: Dimensions of Arm Holes in Concept - v2.3

This design had a bin on the outside to place the non-contact thermometer when not in use. This feature removed the need of having a manufactured window slot. The design also incorporated a minimalistic slot where the saliva sample may be placed when the healthcare worker gives the vial to the patient. This feature is the blue tube that sticks out from the front wall. The figure below shows a close up of the front panel.

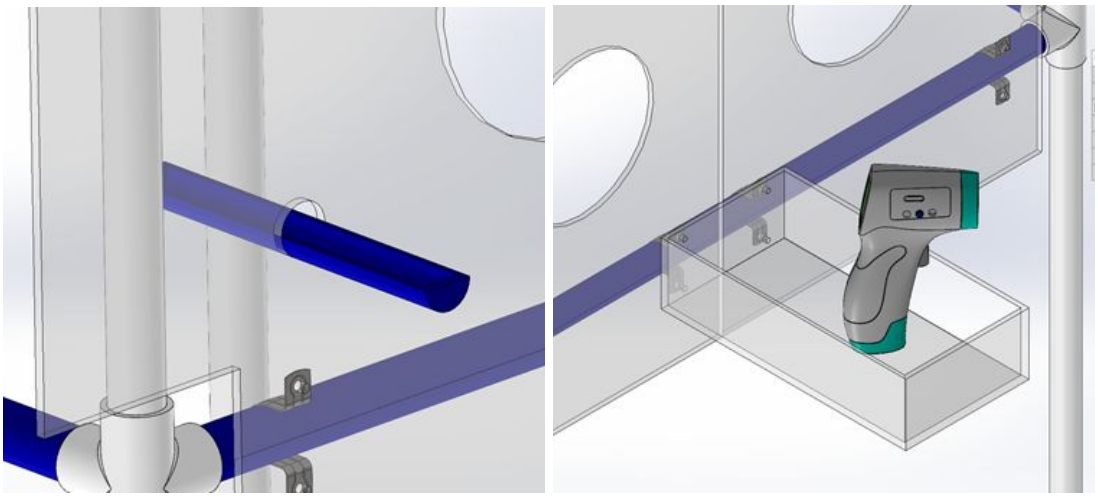


Figure 19: Close-Up of Front Panel of Concept - v2.3.
The left image shows a sample slot and the right shows a plastic bin holding a thermometer.

However, this design showed some issues regarding storage for vials and icebox placement. Additionally, the sample slot was a large risk in terms of transmission protection. The team also decided on one version for all scenarios which was the non-paved ground version. With this in mind, the team needed to optimize the length of the foot extensions and find the minimum required weight on each extension to prevent the device from tipping and/or slipping.

The team also researched online to find specific rickshaw models that could transfer our booth to and from the testing site. A few examples of rickshaw and tricycle models our team found in active use in Ghana are shown in Figure 20. However, we noted that these and many other models could not accommodate our booth's full size when fully assembled (2.11 m x 1.08 m x 1.13 m). For this reason, we decided to allow the booth and its components to be broken down into a more compact form, which would then allow for improved storage and transport in many different vehicles in Ghana.

Figure 20: Potential Tricycles or Trailers to use for Transportation of the Booth in Ghana [48],[49]

These new iterations led to the team's latest, and currently selected, version, Concept v2.4, which is discussed in more detail later on in the report.

SOLUTION DEVELOPMENT AND VERIFICATION

Engineering Analysis:

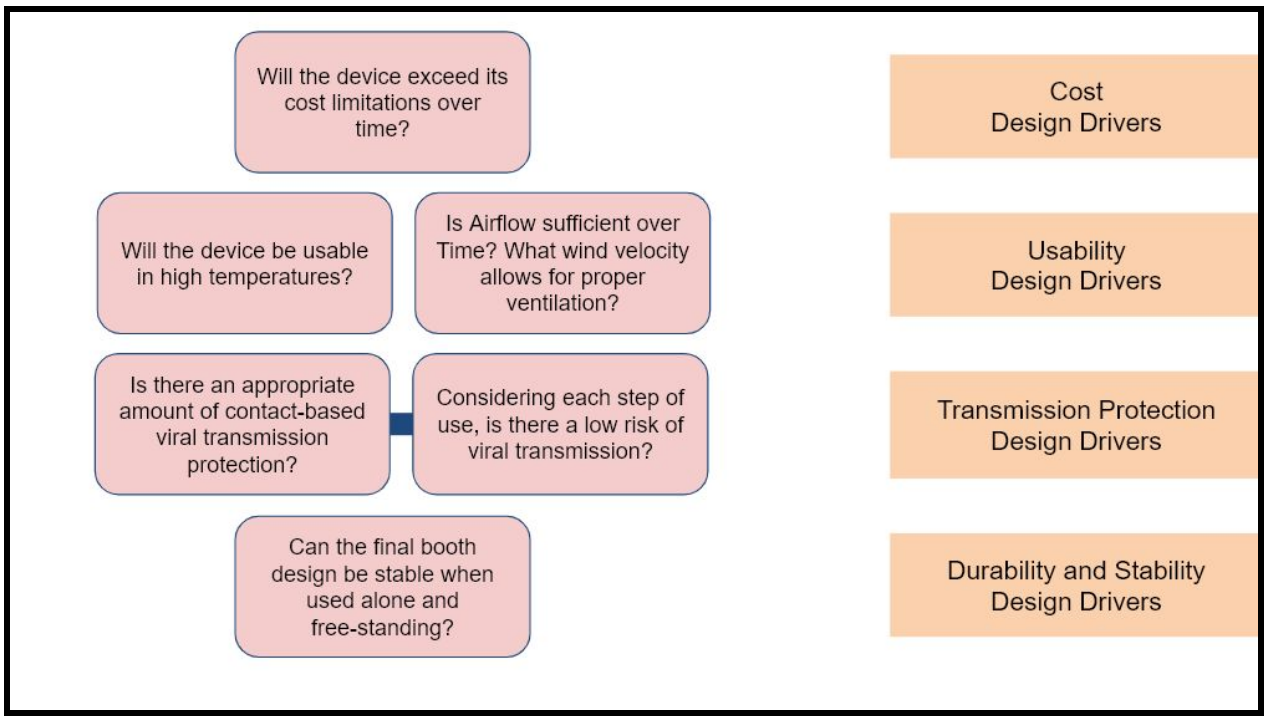


Figure 21: Design Drivers Overview

When evaluating our team's selected concept and its feasibility, the list of the key design driver questions shown in Figure 21 was developed. By considering these questions, we could determine if the booth concept we have in place would be worth pursuing or if any design changes were necessary before moving forward. We performed various types of analyses with each of these design drivers, including theoretical calculations and a risk assessment. The rationale for pursuing each design driver is shown below, and detailed analysis (or planned analyses) and the steps are outlined in the coming sections.

Table 2: Rationale for Project Design Drivers

Design Driver	Rationale
Will the device be usable in high temperatures?	Our team chose this design driver because of a high priority requirement and consideration from our stakeholders that the device must withstand high temperatures in Ghana. If the device cannot accommodate caregivers then the design would not be effective. Internal booth temperature must also be kept comfortable for users[3]
Is airflow sufficient over time? What wind velocity allows for proper ventilation?	Our team focused on airflow in particular because this would initially help counter any increase in temperature inside the booth. At the same time, our final device needs to provide sufficient airflow to allow caregivers to breathe easily. In terms of wind velocity, Ghanain winds are typically ranging from 3-5 m/s, and we wanted to ensure that airflow was sufficient based on the most frequent wind speeds seen in Ghana[50]. This driver would come to affect the shape of our booth design.
Is there an appropriate amount of contact-based viral transmission protection?	As one of the main requirements for our device, viral protection is incredibly key to our stakeholders and the process of testing. There must be minimal to no risk associated with the use of the booth and interaction with booth gloves or sample vials by both the patient and caregiver, as prevention of viral transmission is essential to prevent further virus spread.

Considering each step of use, is there a low risk of viral transmission?	To more broadly consider viral transmission by air or other interactions, we also incorporated this design driver. Each step of usage with the booth must not increase the risk of transmission in any way, and users must be able to perform each task in a safe manner. This will also help ensure our device is user-friendly and protective.
Can the final booth design be stable when used alone and free-standing?	This would help ensure our device has a low risk of falling or breaking, which is important to the desired stability requested by our stakeholders. Because the ongoing COVID-19 crisis may be present for months, we will need to ensure our booth remains stable in wind or other additional external forces.
Will the device exceed its cost limitations over time?	Our problem statement specifies that we require a low-cost solution for testing interactions. Our team was given a budget of $853.00 by our stakeholders, who wanted to make sure our device would be able to stay below this upper cost limit throughout its lifetime. This includes the manufacturing, transport, and usage phases of the device and not only the costs of the device's separate components. Establishing a low cost would also allow us to serve the greatest number of people and the high testing need in Ghana.

Design Drivers

Design Driver #1: Can the final booth design be stable when used alone and free-standing?

Firstly, a back-of-the-envelope calculation with a force/moment analysis was used to determine the weight of the booth required to prevent slipping or tipping. This mode of analysis is theoretical and of a simpler level of detail, as the three-dimensional booth is represented as a two-dimensional free body diagram (shown in Figure 22 below) to better understand the forces acting on the device. Our team wanted to ensure our device could withstand accidental pushes/shoves (noted as a 100 N force) and wind forces (shown as a force distribution) while deployed. With regards to design consequences, this analysis provides a sense of the minimum

weight requirement needed based on external forces from accidental contact or pushes, wind forces, and friction. This also helps determine if the current surface area of the booth is adequate for stability considering wind forces, since those forces are dependent on the surface area contacted.

The FBD shows dimensions $d_1, d_2, d_3, and\ d_4$, which have been sourced from our most recent booth concept and represent height, width, length, and open booth area height from the ground up. A handful of assumptions were also incorporated here:

- Weight is assumed to act at the center of mass for simplification. In reality, the center of the booth is empty space, but this has been done to simplify the two-dimensional analysis. The weight of the caregiver is also not considered here either.
- A static coefficient of $\mu_{static} = 0.18$ was used for the interaction between polyethylene and dirt surfaces. Only static friction and forces were considered for this model. Polyethylene was used as a substitute for PVC, and this is reasonable because of the common usage of polyethylene in pipes just like PVC along with their similar surface texture[51]. This is also a low static coefficient, which has been used for a more extreme case scenario where the friction force is less able to resist an incoming 100 N force.
- A 100 N force (a stakeholder-defined value), which is a specification for our project, was used to represent a push/shove. This force was placed at the top of the booth to generate the greatest moment about the lower left hand corner, designated point O.
- Wind and its associated forces were incorporated through the use of the dynamic wind equation, where pressure, or force per unit area, is equal to ½ times the density and velocity of air squared. Wind speed was also considered uniform and stable. This assumption is reasonable given that the testing booth is not excessively high and does not actively compress surrounding air. Using a database of wind velocities seen in Accra, Ghana, that was collected in 2013, we chose a wind speed of 8 m/s as an upper limit of observed data[50]. This was to overcompensate for the force wind could produce, but observed speeds are typically 3-5 m/s in Accra.

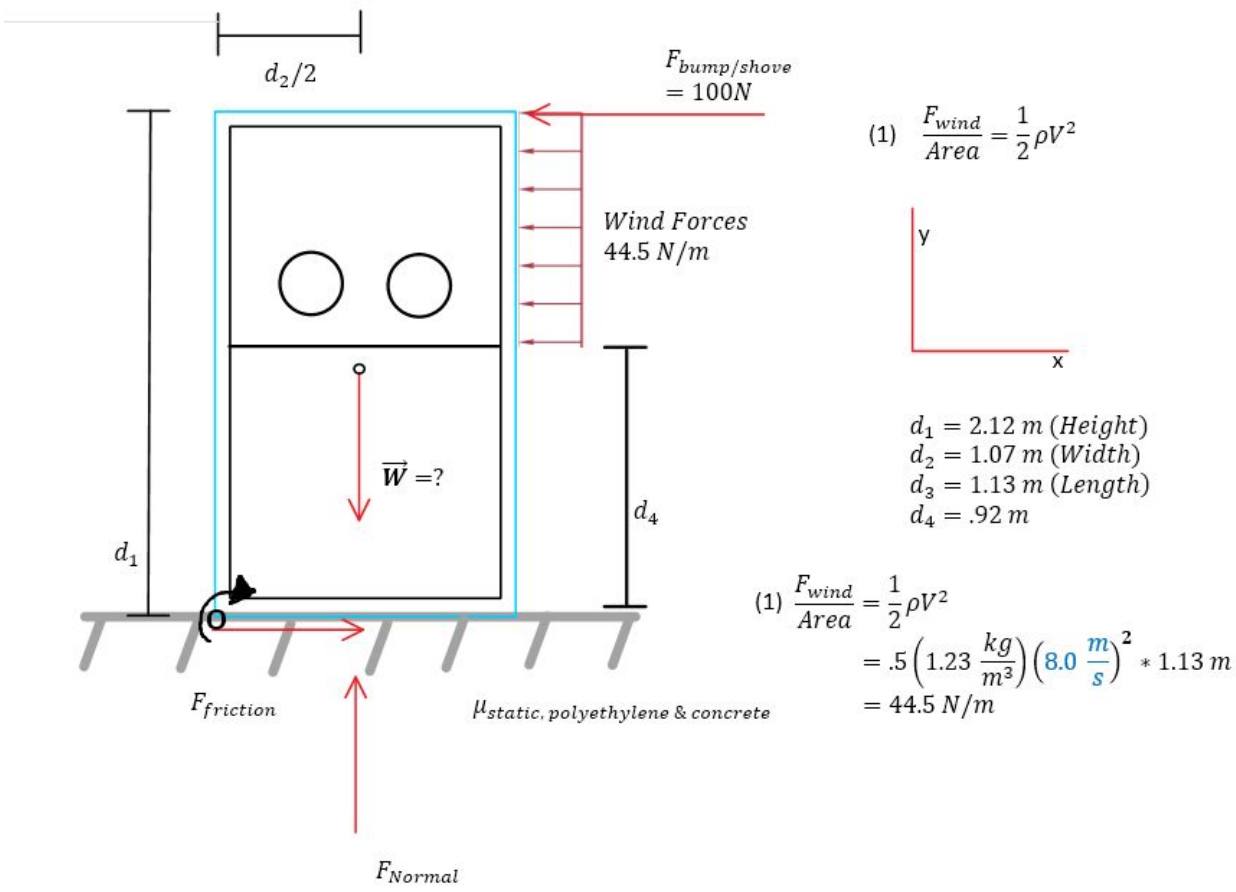


Figure 22: Free-Body Diagram for Design Driver 1

Table 3: Variables Utilized in Design Driver 1 Engineering Analysis

Variable	Definition	Units
d_1	Booth height	m
d_2	Booth width	m
d_3	Booth length	m
d_4	Length of the open area of side panel (from booth base to acrylic panel's bottom)	m
$F_{bump/shove}$	External force from human shove/push that the booth must withstand. Defined based on requirement for stability.	N

$Pressure_{wind} = \frac{F_{wind}}{Area}$	The pressure experienced on the booth surface by the wind. The dynamic wind speed equation was used to calculate this value	N/m^2
ρ	Density of air[52]	kg/m^3
V	Velocity of air. Sourced from records of wind speed in Accra, Ghana[50]	m/s
$\mu_{PE,Soil}$	The static coefficient of friction between polyethylene and soil for the interaction of the booth base and ground beneath it [51]	(dimensionless)
$F_{friction}$	The force generated by friction to resist slipping, dependent on the static coefficient of friction and the normal force	N
F_{normal}	The normal reactive force of the booth that results from its total weight	N
$\vec{W}$	The weight vector of the booth, assumed to act at its center of mass and of equivalent magnitude to the normal force	N

Firstly, the pressure per unit area was found for a given density and wind speed. This calculation resulted in a $\frac{F_{wind}}{Area} = Pressure = \frac{1}{2}\rho V^2 = \frac{1}{2}(1.23\ \frac{kg}{m^3})(8.0\ m/s)^2 = 39.36\ N/m^2$. In the free body diagram, this value was multiplied by the length of the booth (which is a dimension into and out of the page) to convert this value from a force per unit area into a force per unit length that is then suitable for a 2D force analysis. As shown above, this led to the following result:

$Pressure * Length\ =\ 39.36\ N/m^2 * 1.13\ m\ =\ 44.5\ N/m$. This value was used to represent a force distribution along the clear panel of the side of the booth.

The calculation subsequently performed is shown and detailed below. The final outputs include (a) the minimum weight necessary to prevent tipping and moment generation and (b) the

minimum weight necessary to prevent slipping and overcoming friction. If our design was able to exceed the weight requirement for whichever analysis produced the largest required weight, then the design could be considered stable with the forces present.

With a $\mu_{static} = .18$

$F_{friction} = \mu_{static} * F_{normal}$ (2)

$F_{friction} = \mu_{static} * F_{normal} > 100\ N + 44.5 \frac{N}{m} * (2.12 - .92)$

$F_{friction} = \mu_{static} * F_{normal} > 152.96\ N$

$F_{normal} > \frac{152.96}{\mu_{static}}$

Hence,
F_{normal} must be at least 849.78 N to ensure friction is not overcome and that the booth remains static and does not slide.
This requires a **weight from our booth of at minimum 86.624 kg** (190.97 lbs) to resist a 100 N shove and wind force, which is our requirement.

Secondly,

$\sum_{Moments} = 0$ ↺+ (3)

$F_{\frac{bump}{shove}} * d_1 + 44.5 \frac{N}{m} * (1.19\ m)(1.515\ m) - |\vec{W}| * \frac{1}{2} * d_2 - M = 0$

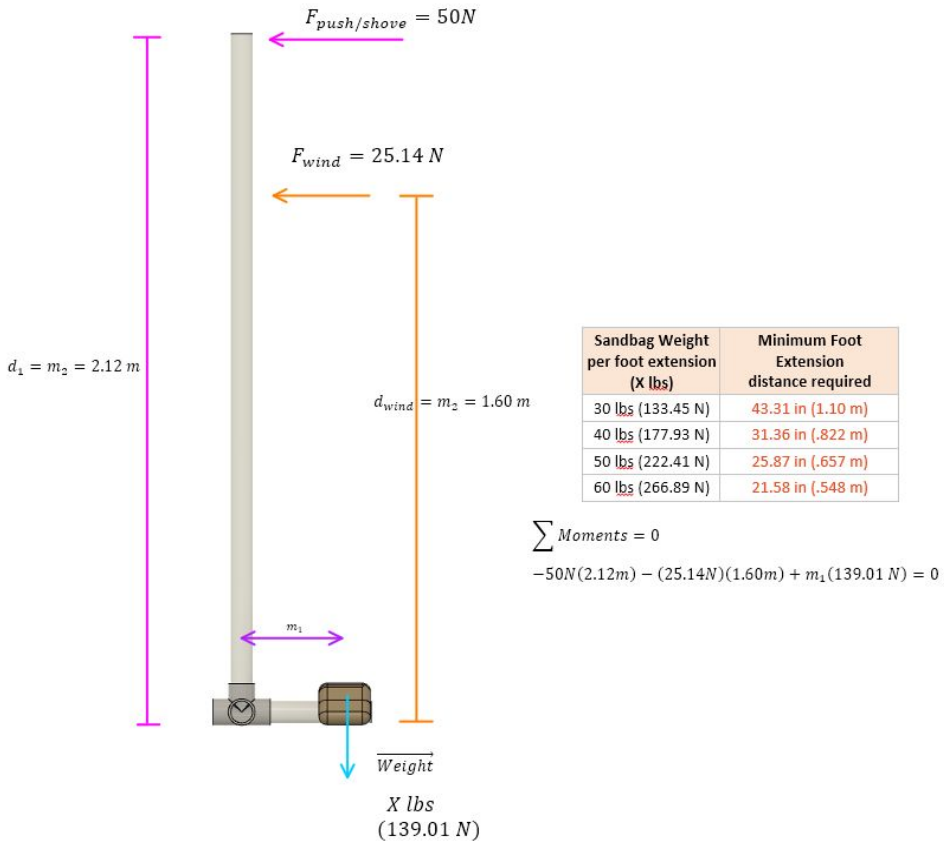
Desired M is equal to 0. For a $F_{\frac{bump}{shove}}$ = 100N, $d_1 = 2.11\ m\ and\ d_2 = 1.08\ m$
The required minimum magnitude of weight needed is ~ 539.31 N. This requires a **weight from our booth of at minimum 54.98 kg** (121.20 lbs). This is lower than the required weight from the friction/force summation.

Figure 23: Calculations of Force/Friction Analysis and Tipping/Slipping Analysis

With the current weight of our design at ~ 66.1 lbs, this booth would not be functionally stable in high winds and forces considered in this analysis. As a result, our team considered a design modification where foot extensions were added as an anchoring location for sandbags and additional weight. Ultimately, the added weight would need to increase the unit weight to at or above 190 lbs.

There is a good level of confidence in this analysis given that our team focused on more extreme scenarios, which we believe will incorporate an inherent safety factor for our final design. At the same time, some technical limitations that may be present include our neglect of internal material failure and assumption that the PVC frame is rigid and can withstand these given loads. Lastly, there are likely also force or moment considerations that cannot be observed in a 2D model compared to an actual model, but regardless, we believe this analysis is a good initial step to determine baseline requirements for our model.

For the design of the foot extensions, our team performed a similar force analysis focusing on the 4-way PVC connectors to determine the length of foot extensions required for a given sandbag weight (and using a tipping analysis). Assumptions included here were that sandbag weights would act as point forces at their centers of mass, forces experienced by wind and pushes/shoves on either side of the booth would be shared equally between the two foot extensions and sides (allowing the analysis of one corner of the booth, assuming the wind forces and push/shove forces are halved there). Booth weight was also assumed to act along the vertical PVC pipe corners, creating a moment arm length of zero meters for the booth weight. Additionally, because a total booth weight of 190.97 lbs was needed and the testing booth weighed only 66.1 lbs without support, an **additional 124.87 lbs minimum** would be required from the sandbags at all four foot extensions. This meant our team needed to consider ≥30 lb sandbags. The free body diagram used in this analysis is shown below, with $\mathbf{m_1}$ as the length of each foot extension and the unknown to be solved for. Sandbag weights of 30, 40, 50, and 60 lbs were assumed to determine the minimum foot extension distance required for booth stability and prevention of tipping.



Sandbag Weight per foot extension (X lbs)	Minimum Foot Extension distance required
30 lbs (133.45 N)	43.31 in (1.10 m)
40 lbs (177.93 N)	31.36 in (.822 m)
50 lbs (222.41 N)	25.87 in (.657 m)
60 lbs (266.89 N)	21.58 in (.548 m)

$$\sum Moments = 0$$

$$-50N(2.12m) - (25.14N)(1.60m) + m_1(139.01\ N) = 0$$

Figure 24: Foot Extension Force Analysis Results

As a result, the minimum foot extension length needed decreased as sandbag weight increased. Our team calculated four different foot extension distances for each sandbag weight. Based on the availability of PVC pipe lengths, we chose to incorporate **40 lb sandbags** and **foot extension distances of .822 meters.** We believe that this analysis was effective given that we used extreme assumptions similar to those earlier in our analysis, namely that both the push/shove forces and wind forces are considered to act simultaneously, and the booth weight is not considered to help offset any tipping moment in this case. This is likely not the case in reality, but this allows for an inherent safety factor in our design once again.

Design Driver #2: Is airflow in the booth sufficient over time?

The specification for our airflow requirement states that our final design requires 0.35 air changes per hour. Therefore, the design driver for airflow was focused on achieving the minimum necessary air changes per hour. In order to address this driver, we decided to utilize the continuity equation to determine the maximum wind speed required to generate the necessary 0.35 air changes per hour. The form of analysis was primarily analytical. This mode of analysis was appropriate because the continuity equation provides sufficient information to estimate the magnitude of the required wind speed. While a computational approach, like using COMSOL, might provide a more complete solution by taking into account the internal geometry of the

device (i.e. glove holes and edge turbulence), the magnitude of the overall solution would not be changed. This is because the overall area covered by the glove holes and box edges is negligible when compared to the volume of the booth and the area of the open slots.

The design consequences of this analysis are that it will allow us to determine if the geometry of the booth is sufficient or if we need to make alterations that encourage further airflow. This consequence, in turn, will allow us to determine the overall amount of material needed to construct the booth. Therefore, at the end of the analysis we will be able to conclude if we need to change our design dimensions. The figure below illustrates our control volume of interest, which is the booth. The problem was modeled by having wind flow in from different directions such as from left-to-right or front-to-back. The front-to-back scenario is displayed in Figure 25 along with the dimensions of the box. The "0.35 air changes per hour" term was converted into a flow rate term using equation (4). Then the continuity equation outlined below in (5) and (6) was used to determine the wind speed required to achieve 0.35 air changes per hour. The highest wind speed required to achieve our requisite air change was then chosen.

$$Q = A(\vec{v} \cdot \hat{n}) \quad (4)\ [52]$$

$$\dot{m}_{in} = \dot{m}_{out} \quad (5)\ [52]$$

$$\dot{m} = \rho Q \quad (6)\ [52]$$

The assumptions used in this analysis state that the fluid (or air) is relatively incompressible, or that the fluid's density remains constant. We also assumed that the flow was steady, or that the wind speed did not vary with time. Finally, we assumed that the wind was uniformly distributed over the surfaces of the booth. The assumption of incompressibility is reasonable given that the container is not excessively tall and does not actively compress the air.

Table 4: Variables Utilized in Design Driver 2 Engineering Analysis

Variable	Definition	Units
$\dot{m}$	Mass flow rate of a fluid through a surface	kg/s
Q	Volume flow rate	m^3/s
ρ	Density of air [52]	kg/m^3
A	Surface area of openings	m^2

$\hat{n}$	Unit normal vector of surface area openings	(dimensionless)
v	Velocity of air	m/s

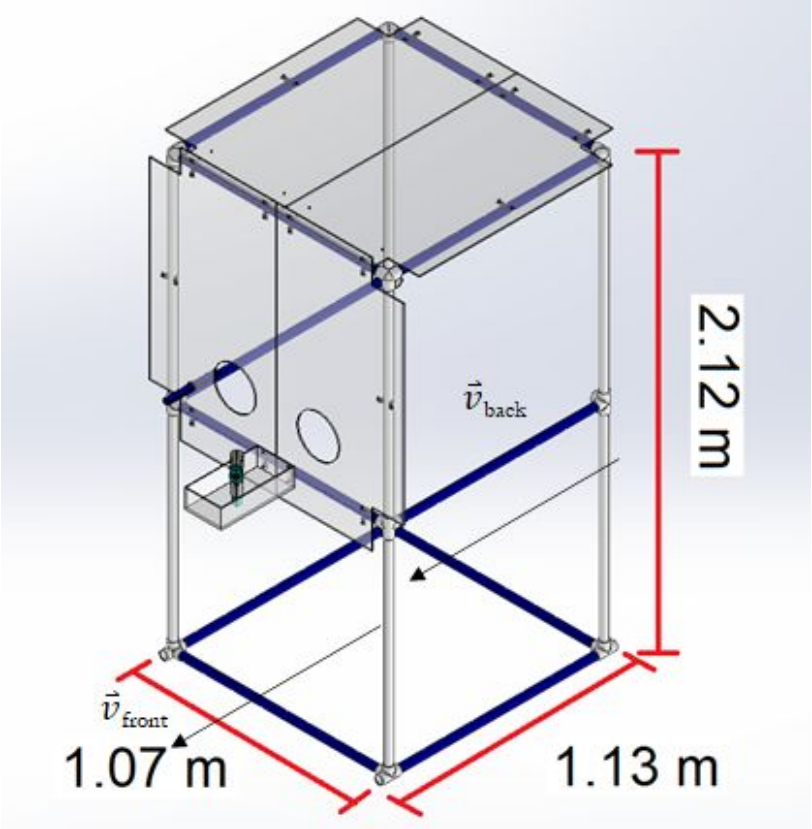


Figure 25: Diagram of Airflow through Booth with a Front-to-Back Wind Scenario.

The specific calculations are provided in Appendix C. In conclusion, a maximum wind speed of $2.73*10^{-4}$ m/s is required to achieve 0.35 air changes per hour. Given that the average wind speed in Ghana is ~5 m/s, this condition is easily met[50]. Therefore, the current booth dimensions and geometry are adequate. One of the limitations of this type of analytical analysis is that it does not account for scenarios with no wind where air is renewed through diffusion alone. It also does not look at the effect of turbulence caused by the edges of the box. Finally, it cannot account for the unsteady, random changes in wind speed. However, despite these limitations, we have a high level of confidence that this analysis allows us to answer our design driver. Given that the magnitude of wind required is so small, even if there are periods of time with no wind, the overall effect on the air changes per hour should be negligible. Using the same reasoning, even if the wind speed is unsteady and time-dependent, it should not significantly change the mean wind speed. Therefore, no further analysis is needed for this design driver.

Design Driver #3: Will the device be usable in high temperatures?

Table 5: Variables Utilized in Design Driver 3 Engineering Analysis

Variable	Definition	Units
P	Mass flow rate of a fluid through a surface	$(kg*m^3)/s$
g	Acceleration due to gravity	m/s^2
z	Height of streamline	m
h_L	Loss of heat due to friction	J
w_S	Work put into the control volume	J
Q	Volumetric air flow rate	m^3/s
ρ	Density of air	kg/m^3
C_p	Specific heat of air	kJ/(kg*°C)
h_a	Coefficient of air convection	W/(m*°C)
A_T	Total surface area of acrylic	m^2
w	Thickness of wall	m
$\widehat{q}$	External heat generation due to Sun	W/m^2
A_s	Surface area of acrylic exposed to Sun	m^2
k	Thermal conductivity of wall	W/(m*°C)
T_a	Ambient air temperature	°C
T_f	Unknown internal air temperature	°C

The purpose of this design driver was to determine if the device could cause the caregivers within it to overheat by trapping heat from sunlight and raising the internal booth temperature.

The attempted solution to this problem was to modify the geometry of the booth to increase airflow, which would theoretically cool the interior of the booth down to a level that was near to the external temperature. In order to properly analyze this design driver, we needed to account for the potential sources of heat within the container. The primary source of temperature change for our device would be radiant heat from the sun. The team found sources that quantified the heat energy produced by the sun as 1,370 W/m^2 and found a set of equations that allow us to relate the cooling effect of airflow to external heat production[53]. However, another potential source of heat within the container could be heat generated due to the friction caused by air flowing through the container. To model the relationship between frictional heat gain and air flow, we were able to use the extended Bernoulli's in equation (7) and its derivative form in equation (8).

$$\frac{P_1}{\gamma} + \frac{{v_1}^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + z_2 + h_L + w_s \qquad (7)[52]$$

$$h_L = \frac{{v_1}^2}{2g} - \frac{{v_2}^2}{2g} \qquad (8)[52]$$

The assumptions involved in this analysis are the same behind the extended Bernoulli's equation. Namely, that the fluid is incompressible, that we have steady flow, and that the results are applicable along the same streamline. A diagram of the situation is provided in Figure 26 below. The figure also includes heat generation due to the sun.

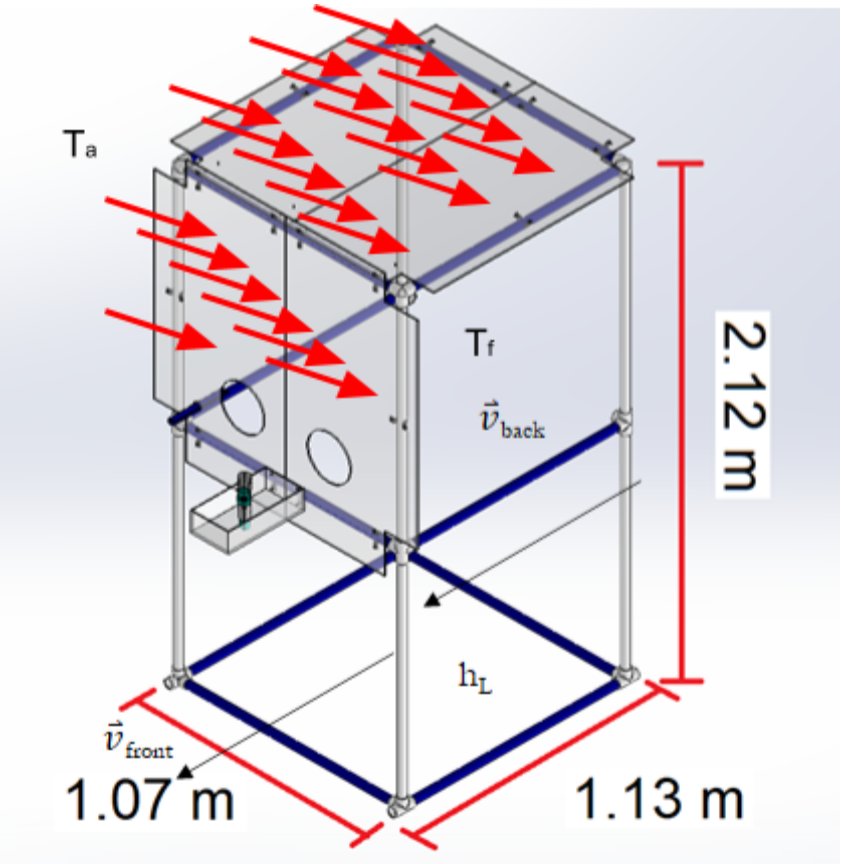


Figure 26: Adapted Diagram of Airflow through Booth with a Front-to-Back Wind Scenario. In this adapted diagram the heat transfer due to friction is considered, as well as the ambient temperature and external heat generation due to the Sun. The arrows indicate the surface area, A_s, that is primarily affected by the Sun.

In order to calculate the effect of the Sun on the internal temperature of the booth, equations (9) and (10) below were sourced from a textbook dedicated to heat transfer across and through surfaces [54]. Equation 9 is referred to as the energy balance equation.

$$\hat{q} * A_s = (Q\rho C_p + \frac{A_T}{R_T})(T_f - T_a) \quad (9)[54]$$

$$R_T = \frac{w}{k} + \frac{1}{h_a} \quad (10)[54]$$

The equations were rearranged to solve for T_f, which would be the equilibrium temperature within the booth. This process can be viewed in Appendix R, along with the associated values.

Most of the values were also derived from the book, with the exception of the external heat energy of the Sun which, as stated previously, was found to be 1,370 W/m^2 [53] and the values specific to acrylic, such as its thermal conductivity [55].

The assumptions governing this analysis are mainly concerned with the geometric aspects of the booth. First, we assumed that the sun's energy would be focused on the acrylic panel at the top of the booth. This is a valid assumption because the other sides of the booth are exposed to the air and calculating the effect of the Sun's heat on them would lead to an answer similar to one found by standing outside the booth. Additionally, since the booth will most likely be used in urban settings, it is reasonable to assume that there will be buildings around it. This would prevent the Sun's energy from focusing on the sides and front of the booth. Therefore, by calculating the effect of the Sun's heat on the top of the booth, we can find what the largest temperature differential would be between the outside and inside of the booth. Second, we assumed that the booth's two side walls were fully enclosed. This was done to limit the number of surfaces through which air would flow to the front and back walls. This is also a fair assumption, because the additional air flow introduced by the two side walls would only decrease the internal temperature of the booth. Thirdly, an ambient temperature of 89℉ or 31.67℃ was assumed using the average summer temperature in Ghana [56]. Fourthly, and finally, we assumed that the volumetric airflow through the container was the same as the one found in design driver #2, since that was the minimum airflow required to produce the necessary number of air changes. It should also be noted that these calculations were performed without taking into account the effect of the heat-reflective tarp incorporated into our final design.

This driver is important because it will allow us to determine if our device is able to perform without the use of a powered air conditioning unit. Since one of our requirements involves decreasing operational costs, we are attempting to minimize the use of power-consuming devices such as air conditioning units. This driver will also help us determine if we need to use different materials with different heat transfer coefficients or if we need to change the geometry of the booth to allow for more airflow. Similar to the analysis performed for design driver #2, this mode of analysis is appropriate because the energy balance and extended Bernoulli's equations provide enough information about the magnitude of the heat transfer to determine if we require a dedicated cooling system. Even if this problem were solved computationally, the magnitude of the heat term would not change.

The specific calculations conducted for this design driver are included in Appendix C. For the extended Bernoulli's analysis, we used the most extreme wind speed values from our analysis of airflow to set our velocities to $2.73*10^{-4}$ m/s and $1.25*10^{-4}$ m/s. These values were found to generate a heat loss of $3.0 *10^{-9}$ J/kg. Given that the overall mass of air flowing into/out of the booth per second is $3.087*10^{-4}$ kg, the heat added via friction to the booth per second can be approximated as $9.26*10^{-13}$ J. Given the small magnitude of this heat term, we were able to

disregard friction-induced heat exchange as a factor. The limitations of the extended Bernoulli's analysis are that we are unable to account for the change in temperature due to the sun and are also unable to account for the cooling effect of the wind due to the temperature difference from the outside and interior of the booth.

Moving on to the energy balance analysis we used the volumetric air flow determined in design driver #2 to set $Q = 2.51*10^{-4}$ m^3 /s. Through this analysis we found that the temperature within the booth was 2.56℃ warmer than the temperature outside of the booth. Using the average ambient temperature of 31.667 °C, this would bring the booth's internal temperature to 34.22 ℃ or ~93.59 ℉. This value is higher than our target of 27-30℃. While we do exceed our target range, it should be noted that there are a few factors that may bring the temperature lower when the device is actually tested in the verification stage. Namely that the 2 sides of the booth are exposed to the outside. This would encourage further airflow and increase the cooling effect of airflow. Additionally, the heat-reflective tarp placed on the top and sides of the booth should decrease the amount of heat transferred into the booth by the Sun. Finally, the wind speeds moving through the booth may be higher than those used in this calculation, since these were the minimum values required for proper air exchange in our booth. Overall, this analysis allowed us to determine that the inside of the booth would not be excessively warmer than the outside temperature, even when the Sun's effects are maximal (i.e. direct heat applied to the top surface of the booth). We have a high degree of confidence in our thermal analysis since the equations allow us to account for the effect of wind flow and the effect of the Sun's heat on the temperature of the booth. This allowed us to determine that our geometry and power constraints are adequate.

Risk Assessment

Design Driver #4: Is there an appropriate amount of contact-based viral transmission protection?

The following analyses were performed to ensure that there is efficient viral protection included in our booth. These analyses also brought attention to any risk associated with the use of the booth and interaction with the patient which allowed us to consider design alterations, if needed, to ensure that there is minimal risk of COVID-19 viral transmission. The team decided to first perform a simpler approach of analysis. Therefore, we chose a risk analysis because it is process-based and provides a broader overview of the risks of the tasks that will be taking place within the booth.

The risk analysis, which can be seen below (Figure 27), helped identify any hazards the device could present to the user. In this analysis, our team took into account scenarios where the patient or caregiver could transmit their viral particles to one another during the sample collection process. The risks identified with our booth included the following: having the vials stored inside the booth, gathering patient information, taking patient temperature, transferring the vial through

the slot, retrieving saliva samples from the patient, labeling the vials, and lastly removing the storage container from the booth that the vials will be inside of. Each risk listed is associated with the risk situation that could occur, the likelihood that the situation would occur, the impact the situation would have on the effectiveness of the booth and a recommended action to minimize the likelihood of the scenario occurring.

Risk	Risk Situation	Likelihood	Impact	Action to Minimize Risk
Vials inside booth	The vials being stored inside the open booth could cause them to be contaminated from dust, rain etc. The samples could also rise above the required temperature of 2-8°C which would make them inadequate.	Low	High	The booth will have a roof and 3 walls that help protect the booth from the environment and vials will be stored inside storage containers that would maintain an adequate temperature for the vials as well as provide additional protection from dust and rain.
Gathering patient information	If the patient is positive for COVID-19 they could possibly transfer the virus to the caregiver while the caregiver is gathering their information.	Very Low	High	The caregiver will be inside of a 4 wall booth and will communicate with the patient through a clear PVC wall while both users are wearing masks.
Taking patient temperature	The patient, if positive for COVID-19, could transfer the virus to the caregiver while their temperature is being taken.	Low	High	The caregiver will open the temperature slot in the PVC wall to use the contactless thermometer to take the patient's temperature which prevents any direct contact at that point.
Transfer vial through slot	While the vial is being transferred between the patient and caregiver through a 'bank teller' slot there could be cross contamination from the patient (if COVID-19 positive) the caregiver could be affected.	Low	High	The caregiver will be the only person touching the vial. The caregiver will put the vial through the slot and then insert their hands in the gloves that are connected to the PVC wall, take the sample from the patient, place the sample in the vial, and then place the vial into the slot transferring it back inside the booth.
Retrieve saliva sample	The caregiver retrieving a saliva sample from a patient who may be COVID-19 positive could cause the caregiver to become infected as well.	Medium - Low	High	We have developed a system of using a 'bank teller' slot that will allow for a great level of protective contact between the patient and caregiver to help prevent any transfer of the virus.
Labeling vials	It is possible if not done correctly that some saliva could touch the outside of the vial.If COVID-19 positive the virus from the vial could transfer to the caregiver while they are labeling the vials.	Low	High	To prevent any transfer of the virus and handling of the vials will be done with gloves and masks on.
Removing storage container	While removing the storage from the booth to the outside of the booth there could be a transfer of the virus to the caregiver and it could also put any other personnel that may be outside of the booth at risk.	Very Low	High	The storage container will be properly disinfected after each sample is placed into it as well as directly before it is transferred out of the booth in order to prevent any transfer of the virus.

Figure 27: Risk Analysis

From this initial evaluation, we first discovered that the process of retrieving saliva samples posed the greatest risk. To try to decrease this risk, we altered our design from version 2.1/2.2 to version 2.3, which incorporated a minimalistic bank teller slot used for the transfer of the sample after it is collected while providing a great level of protective contact between the patient and caregiver. To further decrease this risk, the design was altered once more from version 2.3 to version 2.4, which involved the removal of the bank teller slot and incorporated a table outside the booth, so that all items could be placed outside of the booth. This decreased transmission risk to a minimum since this meant that nothing would then move into and out of the booth.

After evaluating the risk analysis, we felt a Failure Mode and Effect Analysis (FMEA) would give us a deeper insight. We chose to do an FMEA because it is component/hardware-based and focuses deeply on the failure of the device's functionality. This analysis enabled us to identify which feature of the booth in particular had the highest risk of failure. The FMEA, which can be seen below (Figure 28), shows each component of our booth along with the reasons the components could fail, the effect the failure would have, potential things that could have caused the component failure, current controls or methods that were in place to reduce or possibly

eliminate the likelihood of failure, and a recommended action that could reduce the likelihood of component failure to tolerable levels.

The team rated each failure mode for severity on a scale from 1 (small) - 10 (severe), how likely the failure is to occur from 1 (unlikely) - 10 (likely), and how easy it would be to detect this failure from 1 (easy) - 10 (hard). The team went through each risk and assigned the ratings; hence, these ratings might be biased, so we took this into account. Lastly, each component was associated with a RPN which is the product of the severity, occurrence, and detection, and determined the amount of risk the component brings because a higher RPN leads to a higher risk.

Component or Feature	Potential Failure Mode	Potential Failure Effect	Severity 1 (small) to 10 (severe)	Potential Causes	Occurrence 1 (unlikely) to 10 (very likely)	Current Controls	Detection 1 (easy) to 10 (hard)	RPN	Recommended Action
Gloves	Ripped gloves	Decreased viral protection	8	Durability of gloves	5 (Dependent on Material)	Engineering analysis	4	160	Quality check gloves when sanitizing after every use
Wall sheeting	Wind could cause sheets to fly away	Poor environmental protection	7	Not secured well enough	3	Secured by zip ties	2	42	Check the zip ties securing sheeting periodically
	Tear		6	Poor quality cloth. Contact with sharp objects	3	Provided sheet with slack so that it doesn't tear	2	36	Increase strength of plastic sheeting
	Fog up	Decreased visibility	4	Humidity	7	Increased airflow	1	28	Paper towels are provided
PVC cage/base of booth	Collapses	Complete device failure	10	Joints not secured efficiently.	2	Chose right-angle joints	1	20	Checking joints and bars periodically for signs of failure
			10	Deformation or bending of bars.	1	Ensured equal weight distribution	1	10	
Storage container	Doesn't keep vials within correct temperature range	Saliva samples will no longer be able to be used for COVID-19 testing	10	Not closed securely	4	None	3	120	Check that container is closed completely after every use
			10	Defective container	1		9	90	Test containers before use for patients
Non-contact thermometer	Reading is inaccurate or not calibrated	Patient results are invalid.	7	Defective thermometer	1	None	8	56	Test/compare thermometer results before use for patients
	Contamination by patient contact	Potential source of viral spreading	10	Touching the patient skin with the thermometer	2	Established protocol for distance between patient and thermometer	6	120	Sanitize thermometer between patients
Vials	Top not closing securely	Sample becomes unusable. Potential viral spread	9	Caregiver error.	3	Established protocol for vial interaction	4	108	Double check vial before moving it into storage container
	Damaged/cracked vial	Sample becomes unusable. Potential viral spread	9	Dropping the vial	3		2	54	Visually check the vials before sent into field
Swab	Pre-contaminated swab	Viral spread between patients	10	Caregiver error in reusing swabs	1	Established for interacting with patient samples	10	100	Keep new and used vials on opposite sides of booth
		Incorrect test results							
Wheels on booth	Wheels locked up	Booth can't be loaded onto trailer	2	Booth turning too quickly	5	None	1	10	Check wheels periodically
	Wheels becoming loose/fall off	Booth tips over	10	Not assembled correctly	1		1	10	

Figure 28: FMEA Analysis

Evaluating this, the team found that gloves could tear or rip during usage of the booth depending on their material. This posed the greatest risk, with the occurrence score assigned a value of 5, and the severity score estimated to be 8. If the gloves fail, this decreases viral protection for the device immensely. This was expected because the gloves are a key component in the assembly and will be utilized frequently. A key take away from this evaluation is that the material chosen for the gloves is a key factor in the functionality of the device. To address this risk the team decided to use nitrile gloves that are designed to provide protection for the entire arm and are designed to also be chemical and water resistant, which allows the use of diluted bleach solution for cleaning without deterioration. Lastly, the team has designed the booth to include a glove base attachment where the caregiver would only have to loosen a clamp to replace the gloves if

they were to fail. Following these changes, the risk associated with the design is now at acceptable levels.

Design Driver #5: Will the device exceed its cost limitations over time?

The main purpose of this design driver was to determine if the device would exceed its cost limitations over time. It should be noted that we were given a budget of $853.00. Although this value indicates our maximum budget, our stakeholders emphasized that we should attempt to minimize the cost of the device whenever possible. For this reason, we attempted to construct a device that would stay below, or relatively close to, $853.00 across its lifetime. In order to achieve this goal, we cut out units that would actively consume power, and therefore increase cost. The analysis conducted for this design driver was focused on cost analysis. First, a bill of materials was generated and the total cost of the materials was calculated. The bill of materials is located in Appendix B and the total cost was found to be $792.91. While this value is below $853.00, it does not provide the complete picture, since there is also a cost associated with transporting the device to their final destinations. Given that each of the booths will be heading to a different city, the best way to determine the cost of transport was to use the widest geographical span of Ghana as a reference point. At the widest point between its borders, Ghana spans 560 km[57]. We also assumed that the booths would be transferred via mid-size trucks. Finally, there is also a cost associated with the transport of the booth around the city since the booth will need to be transported via road vehicles. In order to estimate the magnitudes of these costs, the Granta Edupack software was used. Using the cost-analysis feature of the software, we were able to generate Figure 29 below.

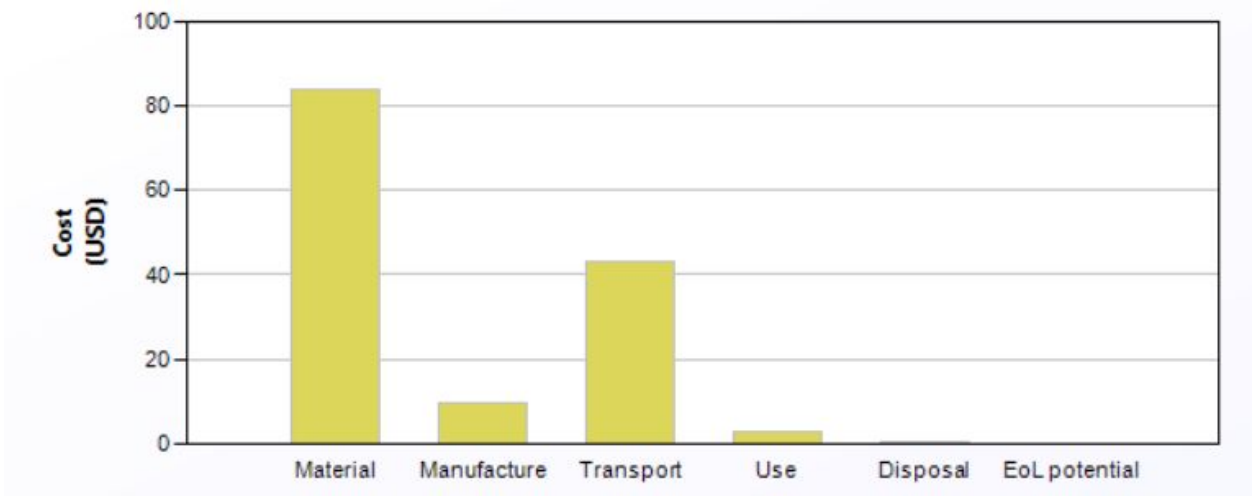


Figure 29: Cost Analysis Over Testing Booth Lifetime

As can be seen in the figure above, the majority of the device's cost comes from its raw materials, with the second highest contributor being the cost of transport. This is to be expected since the device itself doesn't consume much power and the cost of driving it around a city with

a family vehicle is negligible compared to the cost of the materials and transport. Estimating the cost of transport at ~$50.00, and adding it to our total cost from the bill of materials, the overall cost of the device over its lifetime can be estimated at ~$870.50. It should be noted that this exceeds our target price of $853.00; however, this is not a large concern since the cost of transport is what is increasing the price. Given that multiple units can be transported at once, the relative cost of this phase should decrease. Limitations of this methodology are that these values are estimates and must be altered to be specific to Ghana. However, our confidence in the analysis is high because the overall magnitude of the results should remain the same.

Detailed Design Solution

Current Selected Concept- v2.4

This design is similar to v2.3. The only differences is that the team decided to remove the sample slot and the bin on the front panel, incorporate a small table in front of the device, armhole extensions and extend the foot extension in order to place sandbags. Additionally, the team decided to ditch the mobile and minimalist indoor modifications of v2.3. This means that the device is solely focused on the non-paved ground iteration.

The sample slot was removed in order to increase transmission protection in the device. The idea of the sample slot was to pass a sample vial to the patient, but if the vials are placed outside, then there is no need to have a slot. This slot also increased viral transmission rate since this small opening exposes the healthcare worker to the patient. This modification was brought to light during meetings with professionals and stakeholders.

The bin on the front panel was also removed, since the team was now interested in storing components outside the device. This led to the incorporation of a table that is placed in front of the front wall of the device. The device is meant to hold the icebox, the non-contact thermometer, and sample vials that would be placed on the bin. The idea of transmission protection still persists in this modification. The idea is to protect the healthcare worker from transmission when handling the vials. The healthcare worker would simply lift the lid of the icebox, from the inside using the gloves in the armnoles, and the patient would place the vial inside the icebox. Safety protocol is a key step when handling the vials to ensure vials are sanitized prior to being placed inside the icebox.

The foot extensions were extended in order to fit sandbags and prevent the device from tipping and slipping when faced with a troubling Ghanaian environment. This scenario represents a harsh scenario that the device might have to undergo. Engineering analysis was used to figure out optimal dimensions required to ensure that the device did not move using assumptions of very strong Ghanaian wind patterns. The foot extension dimensions were calculated and the weight of each sandbag was taken into account for this calculation. The team decided that the

optimal size for the foot extension is 43.31 inches which requires 40 lb sandbags on each extension. This would help make sure that the device stays in place.

The armhole extensions allow the assembler to pull gloves through the armholes and wrap them around the extensions using a hose clamp as shown below. This allows the user to attach gloves to the device and ensure that they stay in place. Additionally, this allows users to switch out gloves, if necessary.

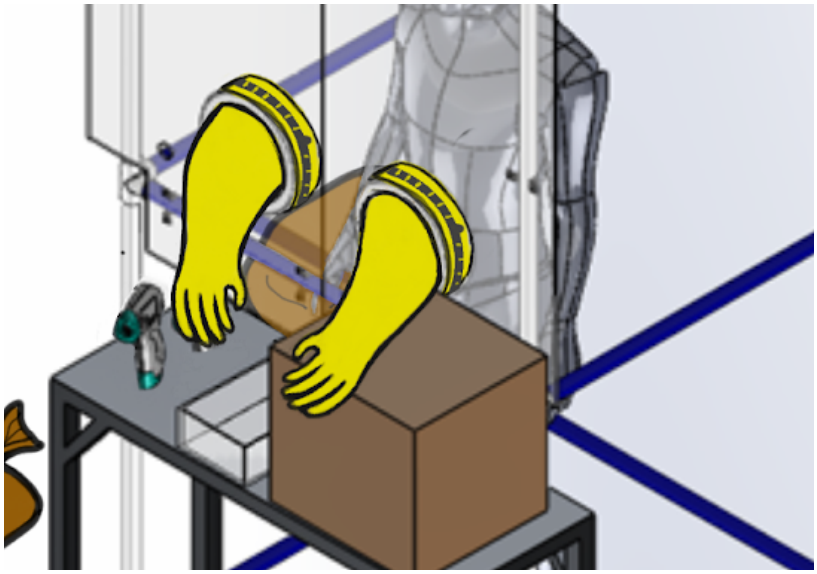


Figure 30: Armhole Extension with Gloves Attached with Hose Clamp

Moreover, the rest of the design is the same as v2.3. This design allowed for a much easier assembly process and is quite adjustable.

This design has a clear wall to view the patient, has arm holes meant for gloves, incorporates a table, the use of a portable ice box, temperature reading capabilities and surrounds the healthcare worker. Figure 31 below illustrates these key features.

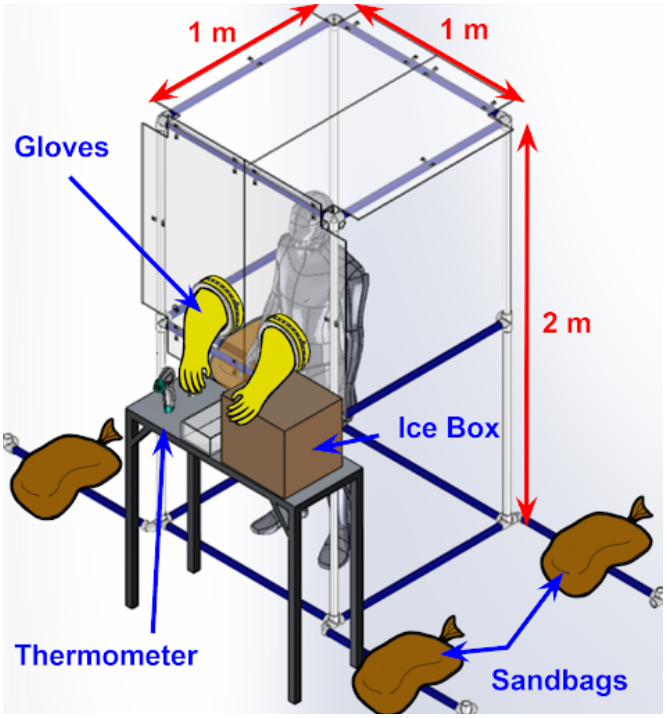


Figure 31: Key Features of Current Selected Concept

In terms of materials, this design still utilizes acrylic walls. One for the front top half of the device, so the patients and caregivers can see each other while still having a physical barrier between them. Another wall is used for the roof, to protect the user from precipitation such as rain. The rest of the side walls will be covered with an adjustable sun-reflective tarp to protect the worker from viral particles, heat, and precipitation, while saving on costs. Figure 15 demonstrates what areas of the device are exposed and Figure 32 shows how the device would look when tarp is attached.

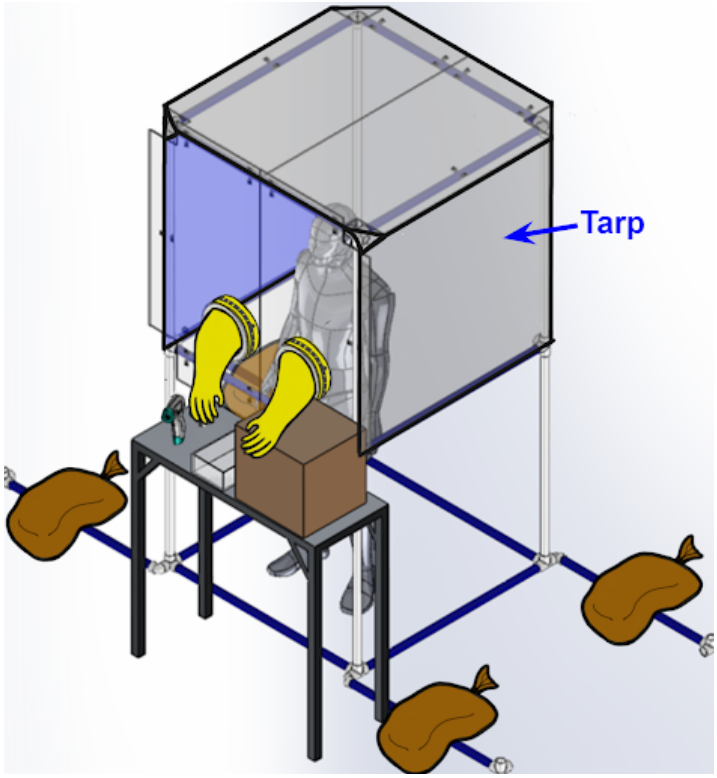


Figure 32: Current Selected Concept with Tarp

This design also has the same booth dimensions as v2.3 as shown in Figure 17. The dimension of the arm holes and the location of them are also the same as in v2.3. The dimension and location of arm holes are shown in Figure 18.

The Bill of Materials, engineering drawings, and manufacturing/assembly plans of the current selected concept, v2.4, are found in Appendix B, G, and H, respectively.

Prototyping of Current Selected Concept - v2.4

The team decided to build a low fidelity prototype to verify dimensions of the device and protocols regarding the usability of the device. The prototype's dimensions are roughly similar to the current design shown in Solidworks. The prototype measures 1 meter (length) by 1 meter (width) by 2 meters (height). Armholes in the low-fidelity prototype are not consistent with the team's CAD, however, their positioning provided information on improved placement of armholes. The chair in Figure 33 represents the table in the team's design meant for the vials, thermometer, and icebox.

Figure 33: Low Fidelity Prototype of Current Selected Concept v2.4 (on the left) with User Interaction (on the right)

Verification

Currently Verified Requirements

Hand Protection

- *Cuff length and protection covers >= 50% of the user's forearm*
- *Pass Purdue Pegboard Dexterity Test*
- *Material used for hand protection can be disinfected with 10-13% diluted bleach solution 50+ times without deterioration*
- *0% direct physical skin-to-skin contact between patients and caregivers*
- *Quality compliant with standards: EU standard directive 93/42/EEC Class I, EN 455,* ***EU standard directive 89/686/EEC Category III, EN 374****, ANSI/ISEA 105-2011, ASTM D6319-10 or equivalent*

This verification was met by design intent and material choice. As seen in our bill of materials, our choice of the Showa 772 nitrile gloves for chemical protection are designed to provide "extended protection for the entire arm," which is well beyond our 50% forearm specification[58]. Additionally, the product datasheet states the gloves are designed for high dexterity and fit, are impermeable to outside materials (which allows for grip while still protecting against skin-to-skin contact and viral transmission), and are compliant with at least one of the permissible minimum standards we have included in our specification (EN ISO 374-1:2016 and EN ISO 374-5:2016). The gloves are also classified at Category III, which also matches the requirement and means that the gloves will protect against risks that may cause very serious

consequences such as death or irreversible damage to health[59]. Lastly, these nitrile gloves are designed to also be chemical and water resistant, and performance levels as per standard 374 are retained after each wash, which also allows the use of diluted bleach solution for cleaning. Gloves of these standards are approved to spend at least 30 minutes exposed to chemicals such as bleach [59]. Since each wash is ~30 seconds, 50 washes would take 25 minutes, which means that the gloves should be able to endure at least 50 washes with our diluted bleach solution. Finally, the standards the manufacturer used for dexterity, while different from the Purdue pegboard test, are comparable in their intensity [58]. More information on the standards can be found in Appendix M.

In terms of limitations, the standards may not hold up to par depending on types of usage and/or these gloves may not be traditionally what medical workers are used to (which may require some adjustment for caregivers). It is also assumed these gloves will not be damaged during assembly and fitting of them to the acrylic wall and holes with the hose clamps.

Low Cost

- *Device costs ≤ $853.00 to make*

By gauging material costs while constructing our CAD model, we found that our testing booth had a final overall material cost of $792.91, which is below our target cost. The detailed bill of materials (BOM) can be found in Appendix B.

This number, however, does not include transportation or labor costs. Once the additional costs are incorporated, the overall cost does exceed $853.00. However, it should be noted that our requirement was only intended to establish the price required to make the device. Additionally, our materials have been sourced from Ubuy, an e-commerce site that serves many international countries. Many of the items included in our final BOM are bought in bulk as well and we believe that individual components can be found in Ghana for a much cheaper price. Thus, we believe that the decrease in costs for our device's raw material will allow for additional costs of transportation and labor while still allowing the device to maintain its unit price of ≤$853.00.

Temperature Reading Capability

- *Uncertainty of ±0.5°C over the temperature range of at least 34-39°C*
- *Stability and drift are less than 0.2°C within a timeframe*
- *Non-contact based determination of temperature*

This specification was fulfilled by the choice of non-contact thermometer that our team made use of. Using benchmarking standards outlined by the FDA, non-contact thermometers are essentially specified to have a temperature uncertainty within ±0.5°C and keep drift down to less than 0.2°C [39]. Because our solution allows for the usage of non-contact thermometers that are

not obstructed by barriers like acrylic, the accuracy of the thermometer is maintained while the caregiver is still protected. Thus, our team had fulfilled this requirement by equipment choice and design intent.

Dimension Limits

- *2.1 m (H) x 1 m (W) x 0.75 m (L)*
- *Device can accommodate patients of 1.496 m height to 1.859 m height (Ghanain population of 5th percentile female to 95th percentile male as per a 2015 study with n= 261)*
- *Device can accommodate 2x the width of the 95th percentile male's hip width distance of 0.418 m (Shoulder or max width dimensions not available)*

Our final device dimensions **1.07m x 1.13m x 2.12m.** By design intent, this accommodates for the height requirements Ghanaian citizens on the interior of the booth, as the 2.12 m height is a value greater than the 95th percentile male height seen in Ghana (an extreme value above average heights for both males and females). With a width of **1.07 meters**, the booth width is designed to be greater than twice the hip width of the 95th percentile male (a larger than average anthropometric measure). Hence, the booth will also be wide enough to accommodate the vast majority of Ghanain citizens.

Verification In Progress Or To Be Completed

All of the requirements in this section require the construction of a fully-equipped prototype or a full-scale, physical booth.

Viral Particle Protection Between Users and Caregivers

- *Full device has the capability to filter 95-100% of particles ≥ 0.3 um*

In order to verify the viral particle protection requirement, we will need to construct a testing set-up similar to those used during mask filtration efficiency tests. First the booth as a whole must be set up in a controlled environment, like a wind tunnel. This will allow us to vary the wind speeds to match the minimum, maximum, and average wind speeds present in Ghana. This will also allow us to determine the range of wind speeds at which the device's viral protection is still effective [60]**.**

The protocol used to test the concentration of viral particles was adapted from those present in relevant literature. First the aerosol particles will be generated using a commercial sodium chloride (NaCl) aerosol generator, such as the #8026 TSI Particle Generator, which can produce particles in the range of tens of nanometers to ~ 5 μm. The aerosol generator will be set up where the patient would usually be standing or ~1 meter from the face of the booth. A particle analyzer would be set up in the same spot to determine the particle size and concentration being outputted from the aerosol generator. N-95 masks target smaller size particles by filtering out at

least 95% of particles ≥ 0.3 μm [18]. Recent studies have also shown that droplets below 5 μm are considered the primary source of transmissions in respiratory infections [61], [62]. Therefore, we will use a # 3330 TSI optical particle sizer (OPS), which measures particles in the 300 nm to 6 μm range, as our particle analyzer. We will set up a second particle analyzer inside the booth, where the caregiver's head would normally rest. Therefore, the analyzer would be set up at ~1.678 m in height and ~0.535 m away from the sides of the booth since that is approximately where the caregiver's head would rest (~the midline of the device). We would then compare concentration and size distribution of the particles upstream (where the patient stands) and downstream (inside our booth). This would allow us to determine if our booth filtered out at least 95% of particles ≥ 0.3 μm.

Isolated & Clear Vocal Communication Between Patients and Caregivers

- *Device allows for vocal clarity and isolation within a 1 meter distance in the range of 40-80 dB (based on 60 dB as the average noise level of human voices and conversation).*
- *Interfaces will have a soundproof rating of STC-35 (loud speech is audible but not intelligible) to isolate patient-caregiver conversations.*

To verify the first specification, it would be ideal to have patients and caregivers in Ghana use and test this booth with bystanders at nearby distances. Each bystander could then be surveyed and asked if conversations were able to be heard or understood. Although this method is subjective, it would be user-focused and help our team assess user satisfaction directly with regards to privacy. The ideal evaluation of vocal clarity would be best judged by users of the booth themselves.

An STC-35 rating means that with respect to sound transmission class, a wall reduces the transmission of sound to its opposite side by 35 dB; normal speech can be heard within a short distance from the wall or enclosure being tested, but speech is unintelligible when patients move away more than a few meters from the booth [63]. Our team chose to use this standard because STC classes are frequently used in industry for soundproof control rooms or acoustic enclosures as an unbiased and numerical test method for sound transmission[63]. A rigorous method such as this one will also ensure that sensitive patient information will not be overheard by anyone other than the caregiver and patient currently being tested, respecting their privacy.

To perform this test, the booth would first be placed in a soundproof room or lab setting. Then, a speaker can be placed at the geometric center in front of our booth (at a fixed preset distance) where it then acts as a source of noise. A constant decibel level of white noise can be played while the speaker faces the booth. Afterward, the registered volume at specified distances from the front wall of the booth would be measured with a noise dosimeter. If the booth demonstrates a 35 dB difference (a transmission loss) on the interior compared to the exterior and greater reductions in sound at greater distances from the booth, then our specification for the STC rating would be fulfilled.

A rather quiet test environment is assumed and used here, whereas actual community settings where the booth is used may have more ambient noise or other noises that can also help in ensuring patient information is not heard a few meters beyond the booth. Limitations of this method may be that a rigorous standard like this would require design changes or more acoustic control if the verification is unmet.

Sample Storage

- *Samples may be stored in refrigeration at 2 - 8^{o} C for 72 hours*
- *Can accommodate up to 1000 isolated samples at a given time*

In order to verify that our icebox will keep our samples at the appropriate temperatures, we could place the icebox in an environment with a similar temperature and humidity to the conditions seen in Ghana. This could be accomplished by using a greenhouse or by shipping the container to our Ghanain sponsors. We would then place body-temperature saliva samples within the box for at least 72 hours. At the end of the time period, we would take the samples and measure their temperature. If the samples were within the 2-8℃ range, the first part of the sample storage requirement would be verified. Additionally, the samples could be tested for viability at research facilities after this time, which would confirm our storage method is effective if samples are able to be analyzed and provide results after this time period.

The second part of the requirement would be fulfilled through design intent, as our team could purchase a certain number of iceboxes as needed for each city/testing location. Even if we are unable to purchase an adequate number of iceboxes due to cost constraints, our sponsors have informed us that Ghana has a refrigerated supply chain, or cold-chain, that allows them to temporarily store samples at various facilities [3]. The samples could be stored in this cold-chain until funds were raised to purchase a larger amount of iceboxes. Here, we have assumed that samples can be adequately stored without breaking, and that sample vials can be labeled and retrieved as needed, so our sample storage method here does not consider methods for added stability and/or current icebox options in Ghana have features that allow for safe transport.

Durability & Stability

- *20 deployments over 6 months*
- *Lasts ≥ 6 months with frequent daily use*
- *Able to withstand 100 N of force generated by user interaction in any direction without parts dislodging or tipping*
- *Able to withstand wind speed of 1-13.5 m/s [Light air to a strong breeze] from any direction without parts dislodging or tipping.*

These requirements may be difficult to evaluate without a physical model in place. The ideal method for verifying these specifications would be to manufacture the booth and engage it in consistent use over six months by deploying it in the field at least 20 times.

For the push/shove specifications, a push-pull force gauge can be used to accurately create 100 N forces at different points on the booth to ensure tipping/slipping does not occur. Additionally, caregivers/patients can also be asked to push or shove the booth intentionally to test its stability in a more subjective way. Our team chose this method since it could incorporate user feedback and also accurately evaluate booth stability in a versatile way. As a limitation, over time and months, the booth performance on this test may decrease, resulting in a loss of stability, and the test may also result in device failure if this specification is not met, which may add to costs and the need of multiple booth models to fulfill this specification.

The wind speed specification would be best evaluated in a wind tunnel with a physical prototype, where speeds can be systematically varied from 0 to 13.5 m/s to test the limits of the booth in higher winds (in a range of speeds typically seen in Ghana) and observe if the unit still remains free-standing and for what duration of time. Limitations regarding this method would include the sourcing of a wind tunnel large enough to place the booth into. We do believe a wind tunnel is an effective and extreme way to model high-speed winds to provide stress to the booth model.

Airflow and Thermal Analysis

- *0.35 air changes per hour but not less than 15 cubic feet of air per minute (cfm) per person*
- *Temperature should be maintained at 27-30^{o}C*

Similar to the durability and stability requirements, the requirements involving airflow and thermal analysis will be best verified through the physical construction of the device.

In order to properly verify our airflow condition, we plan to adopt a type of low-cost air change analysis currently used in healthcare facilities. As with the viral particle protection verification, the device will be placed within a wind tunnel. This will allow us to control the wind speed the device is exposed to and will also let us test multiple conditions. A condition of particular importance would be the air changes created when there is no wind, since that value should be the lowest possible, as all the air is mainly being exchanged via diffusion. Using relevant literature, we found that one of the most affordable ways to properly test the air change within a confined space was to use CO_2 as a tracer gas and to measure the concentration of CO_2 using an infrared gas analyzer, such as the EGM-5 Portable CO_2 Gas Analyzer [64]. In order to test our airflow, we will release CO_2 gas at 13.5 L/min for 5 min. The gas will be released inside the booth at the top of the container. This is because the airflow will be lowest at the top of the container since it is the farthest point away from the open sides of the booth. The infrared gas analyzer will then be used to create a decay curve to determine how long it takes for the air

within the container to return to baseline levels. The gas concentration will also be measured at the top of the container. This value will count as the amount of time it took for a complete air change to occur at the top of the booth, which will be the most conservative value for the booth as a whole. The value will then be converted into air changes per hour, as well as cubic feet of air per minute. The values will then be compared to our requirements of 0.35 air changes per hour and no less than 15 cubic feet of air per minute (cfm) per person. The test can also be repeated 3 times in order to properly verify the results.

In order to measure the temperature within the booth, we will need to place the booth in conditions similar to those found in Ghana. This could be done by either transporting/constructing a booth in Ghana or placing the booth in a temperature-controlled room at the University of Michigan, such as a greenhouse. This would allow us to expose the booth to the conditions that it would be under in Ghana with comparable humidity, temperature, and sunlight levels. Finally, a thermometer would be used to find the average temperature within the booth across its use in a day. Since our sponsors have informed us that the booth would not be operated by one person for more than 12 hours [2], we would look for the average temperature over 12 hours. The test could be conducted under wind conditions similar to those found in Ghana. However it would be most cost-effective to perform the temperature analysis with a wind speed of 0 m/s, since that would be when the temperature differential between the inside and outside would be greatest, since no wind would be provided to carry out the heat introduced by the sun or the person. The test would be conducted to ensure that the average temperature in the booth stayed within 27-30^{o}C.

User-friendly Operation

- *≤ 2 days of training required to learn how to operate/use the device*
- *Zero written commands are required for patient use of the device*

The user-friendly operation condition has already been partially verified. As can be seen in the video of the operation of the low-fidelity prototype in Appendix R, all communication between the caregivers and patients can be performed vocally. Therefore, zero written commands are required for patient use of the device.

In order to determine the days of training required to become proficient with the device, the booth must either be transported or constructed in Ghana. This will allow us to determine how long, on average, it would take a Ghanaian citizen to become comfortable with operating the device. From previous research, we found that proficiency with testing booths would mean that the caregivers should be able to collect samples at a rate of 1 patient per 8 minutes [11]. This time limit would include the time used to disinfect and prepare the booth for the next patient. Once the booth was present in Ghana, our plan would be to provide the caregivers with the protocol present in Appendix J. This, along with the patient protocol in Appendix I, would make up the instructions provided for device operation. We would then perform dry runs with practice

patients to determine if it would be possible for the caregivers to achieve a rate of 1 patient per 8 minutes. If this rate proves to be too quick, changes would be made to the protocol to decrease the time required to interact with patients.

Environmental Protection

- *Compliant with IP55 standard (EN 60529)*
- *Device offers protection from total dust ingress (infiltration) and particles of 0.1- 1 mm size*
- *Protection against low-pressure jets (6.3 mm) of directed water from any angle (limited ingress permitted with no harmful effects)*

This is an additional specification that would require a physical prototype to be best tested. For the Ingress Protection 55 standard (an industry specification), the latter two specifications outline the conditions required for the standard to be met[38]. The primary focus of where our booth would be tested for ingress would be at its seams, or areas where two parts (namely the acrylic panels and their edges) are joined together. Hence, our team would need to ensure that for dust protection, a 1 mm probe cannot enter in between the acrylic panel edges and that user performance is not affected. For water protection, we would need to use low-pressure water jets and ensure that little to no water enters toward the interior of the booth when sprayed.

If this specification is not met, then our product can be modified by adding rubber gaskets or other methods of sealing the booth edges to prevent ingress. We believe this method is an accurate and feasible way to test for environmental protection that is backed by industry guidelines. However, environmental protection might also include more severe weather patterns or humidity that we may not be able to test through these more technical standards.

Rapid Distribution and Deployment

- *$\leq$ 1 hour for set up*
- *Device can be stored at at 1.5m by 1m by 0.5m*
- *Device can be set up by 1 person*

The assembly process for our booth is presented as a booklet of instructions. The device has also been designed to be compacted into a volume that is smaller than the volume of the fully assembled booth (about 1 m by 1 m by 2 m). However, this exact volume for storage space has not been verified or determined yet to be within 1.5m x 1m x .5m as per our specification. This would be done once a physical prototype is created.

The testing booth itself comes apart piece by piece and contains components that do not exceed more than 40 pounds each, so this allows for easy storage and transport. However, a physical model is required to figure out the duration of the set up and the actual compact volume. After constructing a physical prototype in Ghana, we can run usability tests among different Ghanaian citizens to evaluate if one person is able to set up and assemble the booth within an hour, asking them to use our manufacturing and assembly protocols (located in Appendix H). We can also observe this process to see if individuals are able to set up the booth independently and/or

consider changes to our design or protocol if this verification is not met. We believe Ghanaian users in particular, especially common citizens or caregivers, are the best individuals to ask in this situation as they may likely be unfamiliar with this technology and provide a good assessment of how rapidly deployable our solution can be.

With regards to distribution, our team could assemble a few different packages of components using the items in our bill of materials, which would also be an effective way to test device storage. From here, we could formulate dissemination plans to different cities in Ghana, including Accra, by researching methods of transport or shipping available, focusing on the ability of different shipping methods to accommodate our package size.

Material Acquisition

- *100% of materials that produce the final device are available in Ghana*

Materials were sourced from the Ubuy Marketplace. This marketplace has items that may be delivered to Accra, Ghana. The items are either from Ghana or may be shipped to Ghana from external countries. Additionally, if the team is able to visit Accra, Ghana, then the team will be able to explore local markets and buy products locally instead of having to ship products from other countries. Hence, the ideal method for verifying this specification would be to speak with contacts in Accra or ensure each of our components can be found or purchased in Ghana. Communicating with local stakeholders or manufacturers could also help confirm that our materials are readily available in Ghana. Lastly, successful production of a standalone testing booth in Ghana by GSBE without the use of imported materials would also help verify this requirement.

Location of Manufacture

- *100% of the manufacturing steps, including final assembly, can be performed in Ghana*

Manufacturing is required for the armhole extension and acrylic panels due to the holes meant for screws and armholes. Assembly requires a one-time pre-setup which involves gluing acrylic panels together. Afterwards, a flat head or phillips screwdriver is required for assembly and disassembly. The screwdriver is meant for M6 screws which go through U-Brackets. This means that manufacturing may be done in Ghana since there is no need for special hardware. The ideal method for verifying this, once again, would be to allow GSBE to produce a standalone unit in Ghana, and this requirement would be verified if the design and manufacturing is possible.

Non-intimidating Appearance

- *Achieves a score of at least 4 on a 5-point Likert scale that quantifies level of anxiety with medical device appearance*

The team decided to use a certified Likert scale for evaluating the appearance of our testing booth. The Likert scale referenced was designed to capture the reactions of young children in the environment of MRI Scanners and their assessment of the device appearance[42]. This particular Likert scale ranges from one to five. A score of one refers to no fear or anxiety, three refers to an okay reaction, and five refers to strong dislike and preference to avoid. We believe this Likert scale is comparable to our current situation for evaluating a medical device (our testing booth) in terms of its favorable appearance, as the scale also captures the emotional reactions of patients to the medical device (the MRI machine).

The team's ultimate goal score is a four on the Likert Scale; however, using the published MRI Approval Likert scale, the team's desire for a four is contradicting. This means that the team will flip the MRI Approval Likert scale. A score of one will refer to a strong dislike and a five will refer to no fear or anxiety at all. This Likert scale will help the team figure out if the device is approachable or intimidating. This will be done once a complete prototype is created, and caregivers, patients, and other users can be asked in Ghana directly about their evaluation of the booth appearance.

Validation

Our team also believes additional steps for validation with a physical testing booth prototype will help evaluate a few other requirements and specifications in addition to the verification plans outlined above. Specifically, our team would like to test how our booth operates in a realistic setting, how it accommodates patients, and how well it allows the collection of samples by caregivers. To see if our target audience of Ghanaian citizens is satisfied with the product, the booth would need to be both constructed and deployed in Ghana, where our team could then receive user feedback from caregivers and sample collectors as well as patients about their experiences when engaging with our device. Another validation step would include asking users about how understandable our caregiver, patient, and set-up/teardown protocols may be for them (these resources can be found in Appendix J, I, and H, respectively). Initially, we have shown these protocols to one of our primary stakeholders, Dr. Elsie Effah-Kaufmann, and received her suggestions and approval, but the true effectiveness of those guides would be best tested among actual users looking to receive a COVID-19 test or collect samples by use of our booth. Additionally, we believe deploying the booth for 6 months with frequent daily use could also help us identify additional weaknesses or areas of improvement based on feedback from patients and caregivers, allowing us to then consider modifications that could help make our solution more sustainable.

DISCUSSION AND RECOMMENDATIONS

Design Critiques and Current Status

Our team received feedback from our stakeholders and other students in Ghana who stopped by at our Design Expo virtual room to provide their insight. During this time, we had the chance to listen to the first impressions from other students about our design and reflect on our design decisions.

In terms of strengths of our design, we believe our testing is able to provide effective viral protection at a $850 cost which is lower than many of the benchmarks our team had found on the market. With the addition of both a draped tarp and acrylic panel, a caregiver is afforded a good amount of viral protection from their front and sides. We also believe the booth design allows easy movement, set-up, and tear-down options along with deployability in a variety of settings. We mention these strengths with a grain of salt, as a physical prototype has not been constructed, and these characteristics have not been proven to function perfectly. However, these are aspects of our design that visitors during the Design Expo were intrigued by. We also believe a good strength of our design is minimal manufacturing need, as only acrylic panels would need to be shaped/cut, but the remaining structures and booth components can be fixed and assembled by hand. We also believe that our user protocol presentation and instructions are concise and straightforward to follow, but again, the true effectiveness of these depends on user tests and validation. As of now, we have promising qualities that we would wish to test in person with a physical prototype.

With regards to weaknesses, a few visitors during Design Expo mentioned that our design cost is not something hospitals may be willing to pay for purchase of the booth. When sourcing our costs and materials, we used UBuy, an international e-commerce site that allowed for shipping to Ghana, but this site sometimes sold and shipped products that were manufactured outside of Ghana. Hence, our costs may not have been realistic, and we expect lower actual manufacturing costs in Ghana, but this needs further work to research and document. We believe our team could have also spent a bit more time and effort in procuring costs from Ghanaian citizens or vendors during this semester along with additional cost-reduction efforts for specific components. Our acrylic panels were expensive as individual units, and many of our materials were bought in bulk components, which added to cost largely. Additionally, while our design provides viral protection at the respiratory level and above the waist, a large space of the booth is uncovered near the base, which could arguably allow for viral particles to enter and rise into the booth interior. One additional optimization problem and design driver our team could've likely considered is the trade-off between the price of additional acrylic panels or tarp protection and the improved viral particle protection. Lastly, our team also believes that it would've been valuable to contact additional students or professionals in Ghana at earlier stages of the project about topics such as testing needs, sample storage capacity, standard procedures, and other

questions as they arose. We began to pursue this work a bit later in the semester after our main stakeholders were more unavailable or busy with other commitments and received valuable information from some physicians and medical students.

Moving Forward

In the coming semester, it is the goal of a few students on this team to continue the project work in partnership with Ghanaian stakeholders, focusing mainly on building a physical prototype if this is a possibility in the coming semester. This would involve a side-by-side build of a physical testing booth in both Ghana and Michigan, allowing teams to troubleshoot between each other. Our team would also like to pursue cost reduction strategies and explore local manufacturing options in Ghana. Currently, our team is working to find a new space for our project to continue, possibly in a new student organization with a faculty advisor this coming semester. In the future, after a booth prototype has been constructed, the plans and experimentation to verify our requirements should be pursued, and the device should be deployed and used consistently in Ghana once any necessary design modifications have been implemented.

Sponsor Recommendations

We recommend that the next steps beyond creating initial prototypes of our testing booth device would involve implementing usability tests to evaluate our user protocols, caregiver protocols, and teardown/assembly protocols among the Ghanaian population, including both literate and non-literate individuals if possible. This will likely influence modifications to these publications as well but would allow us to improve instructions or recognize common areas of difficulty for users. We also recommend that stakeholders in Ghana or physicians and community volunteers attempt to construct and use the booth in a live setting to ensure materials are readily available and recognize where clarifications in our publications could be added.

With this, we also believe both students in the US and students in Ghana should focus specifically on evaluating requirements such as rapid distribution and development (if the booth can be set up within an hour and by a single person), user-friendly operation (below 2 days of training necessary to learn how to operate/use the device), and durability/stability (test the booth for 6+ months and with 20 different booths deployed to ensure the design is sustainable). The longevity and sustainability of the device will be important in a Ghanaian setting. It would also be important to observe patient-caregiver interactions with the device to determine if any features need improvement or adjustment and identify common mistakes that may occur in our current protocols and plans.

CONCLUSION

In summary, the goal of our project was to design a low-cost, rapidly deployable interface between patients and caregivers that will allow for safe patient sample collection in low-resource

community settings in Ghana while also minimizing the use of disposable PPE. Throughout this semester, we engaged in the design process by defining our problem, developing a solution, and verifying our solution's features/requirements. Our current version involves a PVC tubing frame and 2 acrylic walls that serve as the patient interface and roof respectively. The booth also will employ an external table that will hold the non-contact thermometer, clean sample collection vials, and icebox for short-term vial storage. We also conducted engineering analysis by developing and answering design drivers focused on usability, transmission protection, stability, and cost. Four of our 16 requirements were fully verified by the end of the semester, and plans were developed to test and verify the remaining 12 when the physical prototype is manufactured next semester. In terms of final deliverables we currently have manufacturing & assembly plans, engineering drawings, patient and caregiver protocols, and a fully-developed CAD model to support any future work.

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ACKNOWLEDGEMENTS

Dr. Aubree Gordon
Dr. Kathleen Sienko
Mr. George Boadu
Dr. Elsie Effah-Kaufmann
Caroline Soyars
Marcus Papadopoulus and Dr. Stephen Papadopoulus

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APPENDICES

APPENDIX A : FINAL BENCHMARKING TABLE

The document containing the table is also linked above.

Model/Solution	Method of Protection between Caregiver & Community Member			Actual or Intended Location of Use	Sample Storage Possible?	Methods of cleaning/sterilizing (with reusable solutions)	Filtration Method Present?	Ease of local manufacturing and sourcing materials	Ease of Training	Testing Capabilities	Transferability to Community Settings
	Positive Pressure Ventilation	Negative Pressure Ventilation	Other								
Ansys Testing Booth High Resource Settings	☐	☒	Negative pressure to prevent contaminant leakage. HEPA Filtration system also present [1]	Community sites	No, requires separate boxes [1]	Users can clean all surfaces with a mild detergent or disinfect with bleach.	Yes. Exhaust Vent. 24 air changes per hour [1]	Acrylic Sheets, Alum frame, HEPA filter/blower unit with 125 CFM. Power generator/backup Unit. Rubber gloves, PPE kits separately [1]	Speakphone communication. No written instructions. Knowledge of flowrate may be necessary [1]	Can test one person in 5-7 minutes [1]	Low
K-Walkthrough Sputum Collection Booth (South Korean Design) High Resource Settings	☐	☒	Negative pressure motor blocks the virus coming out of the tester's body from being transmitted to the outside environment [2]. Airtight Booth. UV-C Light runs [3]	Parking Lots under tented shelters [3]	Must be stored separately	5 minute primary sanitization. 5 minute secondary. replacement of plastic protective shield and gloves after sample pickup	Yes. See Columns D:E,F	Not likely possible (UV-lamp. foot sterilizer will likely not be readily available technologies in Ghana). Custom gloves	Relatively Easy (some training on disinfection protocol required and interpretation of pressure gauge, sterilization tools), and communication method to speak with patients [3]	Can be used to conduct 15+ tests per day individually (About 7-15 minutes per test). [3]	Dependent on trained, literate individuals. Requires more expensive equipment and training Designed to be used in specialized medical tents
Eleven COVID-19 Hexapod High Resource Settings	☐	☒	HEPA Filtration system also present to discard cleaned exhaust to outside environment. Patient breaths/coughs, sneezes expelled. Protection shields/panels between patients. Full box barrier for adults [7] No pressure based ventilation.	Outdoor locations with power availability	Yes, vials can be placed in racks on shelves. Patients can leave samples.	Users can clean all surfaces with a mild detergent or disinfect with bleach.	Yes. See Columns D:E,F	Not likely possible (Mass. General Hospital and Engineering design. More robust/expensive equipment [7]	Relatively straightforward usage, but some training on disinfection protocol or proper usage needed	Three different individuals can be tested in one booth. Doc/handle insertions on device for easy removal	Low Delivered in flat packs. Can be assembled anywhere and fixed to the floor with included special slots Could be stacked adjacently
Jacomex Testing Cabin [Designed for mass distribution] All Settings (including, low-, middle-, and high-resource settings)	☐	☐	Rings and gloves are mounted on highly-secure containment enclosures normally designed for the protection of technicians during the handling of nuclear material (and thus company argues this is effective against virus transmission). [4]	Public Places Hospitals, Clinics, blood testing labs [4]	Yes. Internal Shelf Present for sample storage/placement [4]	Non-porous materials with long term resistance utilized in booth, and device designed to be easily decontaminated [4]	No	Aluminum Screws and Brackets, Acrylic panels, Neoprene rubber gloves and some plastic materials. EPDM Rubber. No specialty materials [6]	Easy. Device is walk up and use. No written communication on device, and physicians can guide patients with communication	Limited to one person, but many units can be placed in small areas to facilitate testing	Ships flat. Easy to install. 30 minutes maximum to set up. Flexible to move. Can be used indoors or outdoor [6] Open source and instructions/guidelines available to produce devices anywhere in the world
ROOM - Testing Booth All Settings (including, low-, middle-, and high-resource settings)	☐	☐	No ventilation. Open design without boxed unit. Composed of three walls in 'H' shape. Plexiglass Barrier (recycled from office phone booths). Medical Grade gloves equipped. Gloves are attached directly to the booth using clamp. [5]	Community settings, more uncommon testing locations	Yes. Internal Shelf Present for sample storage/placement [5]	Clean all surfaces with a mild detergent or disinfect with quaternary ammonium products. Be careful not to use products with alcohol, since those can damage the plexiglass. Neoprene that's resistant to vapors, gases, and a broad range of chemicals to protect hands during testing. You can disinfect the gloves using quaternary ammonium products or a bleach cleaning solution.	No	Stainless Steel walls and floor.	Relatively Easy (some training on disinfection protocol required and interpretation of pressure gauge, sterilization tools), and communication method to speak with patients [3]	Can be used to conduct 15+ tests per day individually (About 7-15 minutes per test). [3]	Low
				Refrigeration not inherently possible.							

APPENDIX B: TABLE OF BILL OF MATERIALS

Bill of Materials				
Product	**Description**	**Quantity**	**Price (GHS)**	**Source**
Weld-On 4 Acrylic Adhesive	4 oz of Acrylic Adhesive with Applicator Bottle	1	127	[52]
LetsFix PVC Pipe	Pack of 10 1" PVC Tube (1 m each)	2	690	
Acrylic Sheet	Clear 1/4" 24"x48" Acrylic Sheet	4	1984	
Sellers360 PVC 3-Way	Pack of 10 1" PVC 3-Way Fitting	1	134	
Sellers360 PVC 4-Way	Pack of 8 1" PVC 4-Way Fitting	2	268	
Lasco PVC Spigot	White 1" 90 Degree Spigot Elbow	4	240	
Keadic U-Brackets	Pack of 30 1" SS U-Brackets	1	114	
M6 Screws	Pack of 50 SS Screws	1	91	
Idesign Plastic Storage Organizer Bin	Clear 11"x7"x3.5" Bin	1	121	
B-Air Grizzly Tarp	Blue 8'x10' Tarp	1	85	
M6 Nuts	Pack of 35 SS Nuts	1	70	
M6 Washers	Pack of 100 Zinc Plated Washers	1	65	
Glove Base Attachment	10” Diameter Plastic Cap	2	214	
Hose Clamps	Pack of 2 10” Diameter Hose Clamps	1	74	
Nitrile Gloves	Pack of 2 Nitrile Gloves	1	134	
Table	Plastic Aluminum Table	1	234	
Total			**4645**	**≈ $792.91**

APPENDIX C: CALCULATIONS FOR AIRFLOW AND THERMAL ANALYSIS

Airflow Analysis

$V_{Booth} = (1.13\ m)(1.08\ m)(2.11\ m) = 2.575\ m^3$
$= 2.58\ m^3$

0.35 Air changes per hour

$Q = \frac{0.35}{hour} \cdot 2.58\ m^3 = \frac{0.903\ m^3}{hour} = 2.51\ E\text{-}4\ \frac{m^3}{s}$

Conservation of Mass:

$\dot{m}_{in} = \dot{m}_{out}$

$(\rho Q)_{in} = (\rho Q)_{out}$

Assuming fluid is incompressible...

$Q_{in} = Q_{out}$
$A_{in} \cdot V_{in} = A_{out} \cdot V_{out}$

Wind: Front to Back

$A_{Front} = (1\ m)(0.92\ m) = 0.92\ m^2$ $A_{back} = (2\ m)(1\ m) = 2\ m^2$

$Q = A_{Front}\ V_{Front} = 2.51\ E\text{-}4\ \frac{m^3}{s}$ $Q = A_{back}\ V_{back} = 2.51\ E\text{-}4\ \frac{m^3}{s}$

$V_{front} = 2.73\ E\text{-}4\ m/s$ $V_{back} = 1.25\ E\text{-}4\ m/s$

Wind: Side to Side

$A_{side} = (1m)(1m) = 1m^2$

$Q = A_{side} V_{side} = 2.51E-4 \frac{m^3}{s}$

$V_{side} = 2.51E-4 \ m/s$

Max wind speed needed: $2.73E-4 \ m/s$

Heat Analysis

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$$

$$h_L = \frac{V_1^2}{2g} - \frac{V_2^2}{2g}$$

Using most conservative values...

$$h_L = \frac{(2.73E-4 \ m/s)}{2(9.8 \ m/s^2)} - \frac{(1.25E-4 \ m/s)}{2(9.8 \ m/s^2)}$$

$h_L = 3.08E-9 \ J/kg$

APPENDIX D : DESIGN HEURISTIC CONCEPTS

Heuristic Number (#)	Principle	Modified Concept
4	Add to existing product	Removing and replacing interior of mobile rickshaw (Hollowing out) to house the overall device/booth.
13	Apply existing mechanism in new way	Use power system in tricycle to power devices/refrigeration
30	Divide continuous surface	Divide Umbrella Concept to individual panels
33	Expose interior	Elevate roof of rickshaw so that airflow can be generated.
37	Hollow out	Exchange door in lean-to for curtain to allow more airflow but still have an option of privacy
42	Make components detachable/attachable	Can swivel dividers in lean-to to also serve as overhang for patients in bad weather
60	Simplify	Simply cube concept by removing the roof and back wall. No need for filter or fan
61	Slide	Be able to slide curtains aside in lean-to to increase size of device
71	Use human-generated power	Use a pedal powered fan to provide cooling within the device in cube concept
73	Use packaging	Device contains itself when packaged
77	Visually distinguish functions	Have labeled/colored arrows to indicate what patients should do

APPENDIX E : FINAL MORPHOLOGICAL CHART

The document containing the table is also linked in the title above.

Morphological Chart for Testing Booth		Concepts				
Subfunctions		1	2	3	4	5
1	Provide Respiratory Barrier	Plexiglass	N-95 mask	HEPA-filter	Full PPE suit	(+/-) Pressure
2	Hand protection for Sample Collectors. A method to interact with patients and take samples	Nitrile gloves	Neoprene glove box	Continuous sanitization	Gardening / Work gloves	Above-wrist surgical gloves
3	Clear vocal communication with patients	Loudspeaker system	Radio	Cord phone system	Walkie Talkie System	Pre-recorded message
4	Sample Storage	Refrigerator	Insulation box	Vials and test-tube storage at rt.		
5	Sample Testing	CRISPR Paper test	RT-PCR machine	Antibody Assay	SARS-CoV-2 Antigen Test	LAMP Assay DNA Amplification - LAMP test
6	Protection against dust, water, weather, heat	Roof	Battery Powered Fan	Liquid Repellent	(+/-) Pressure	Enclosed Design
7	Temperature Reading Capability	Non-contact thermometer	Mouth thermometer	Armpit thermometer	Ear thermometer	By hand
8	Rapid Distribution and Deployment	Mobile Unit	Modular design	Lean-to	Inflatable tent	Hinged design
9	Stable and Durable Barrier	Plexiglass	Glass	Sandbag Anchors	Plastic sheeting	Tent Stakes for Fixation to ground

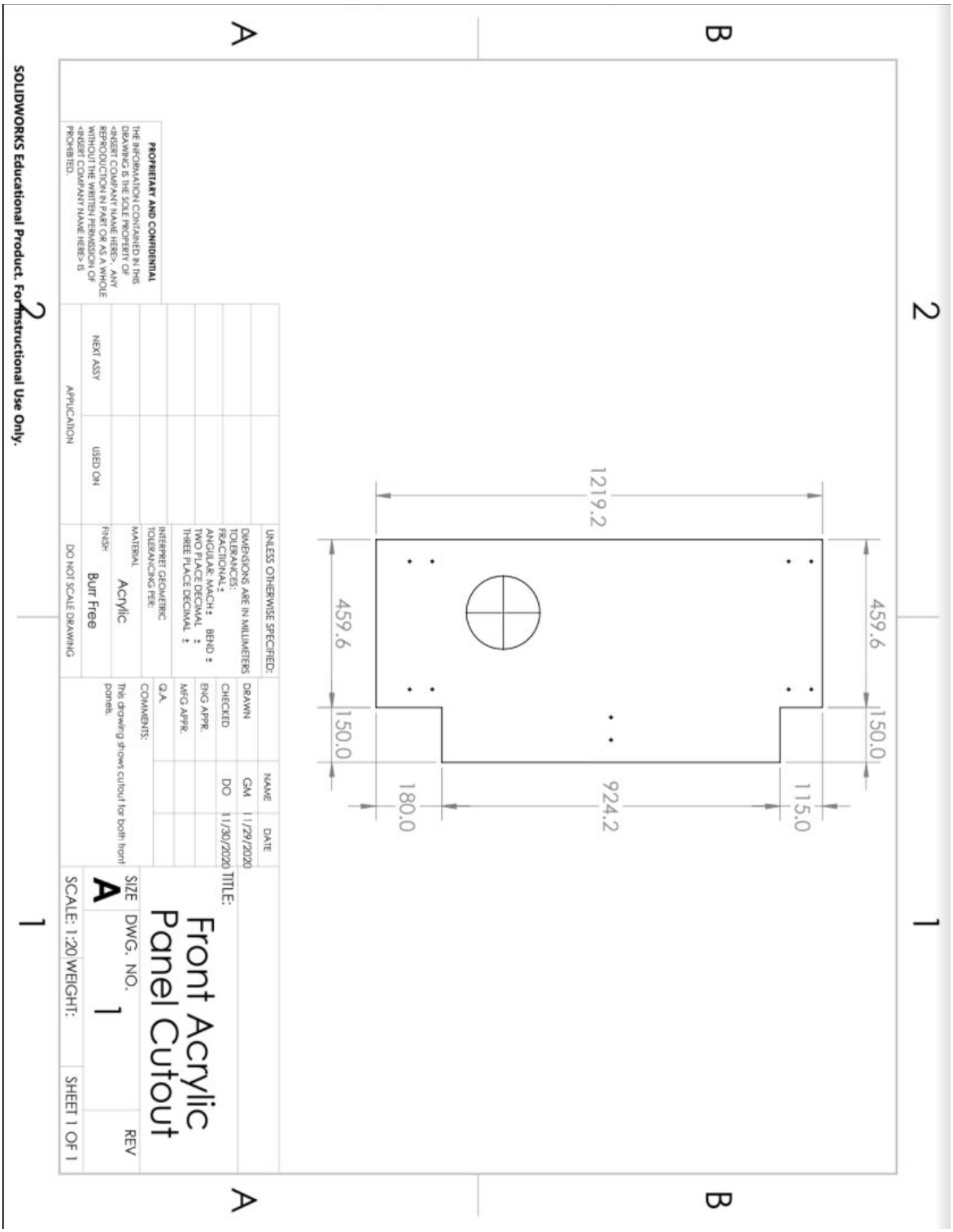
APPENDIX F : FINAL WEIGHTED DECISION MATRIX

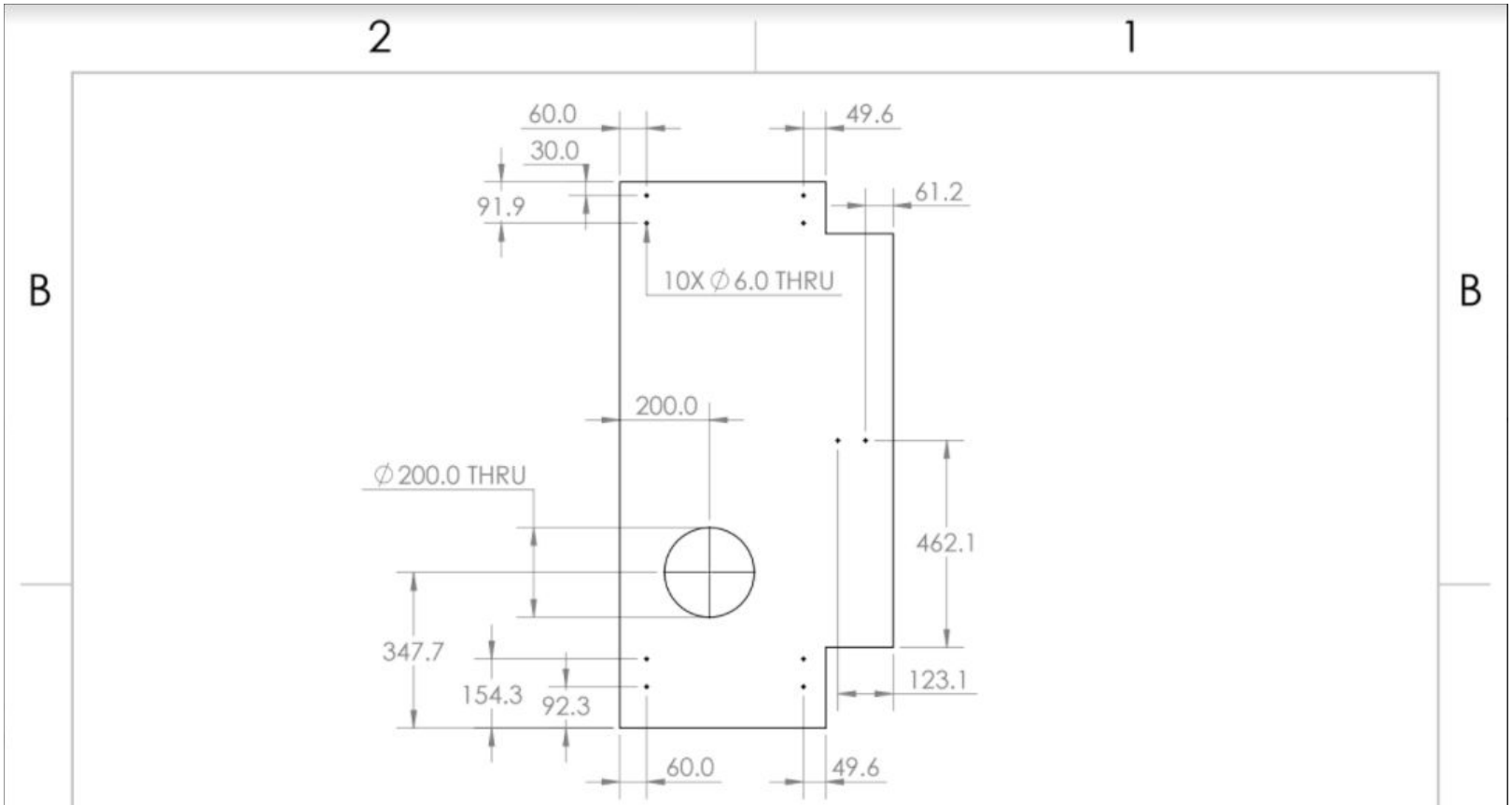
The document containing the table is also linked in the title above.

Weighted Decision Matrix

Design Criterion	Weight Factor	Units	Mobile Rickshaw Concept		Cube Design		Umbrella Design		Leaning Design		Room Design with Added Bar		Modular, 3-sided Design	
			Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Viral Particle Protection	0.175	Y/N	6	1.05	9	1.575	7	1.225	8	1.4	5	0.875	5	0.875
Hand Protection	0.025	Y/N	7	0.175	7	0.175	7	0.175	7	0.175	7	0.175	7	0.175
Clear Vocal Communication	0.025	Y/N	4	0.1	5	0.125	7	0.175	8	0.2	9	0.225	9	0.225
Durable and Stable	0.05	Y/N	8	0.4	7	0.35	6	0.3	5	0.25	5	0.25	6	0.3
Airflow	0.075	CFM	8	0.6	3	0.225	6	0.45	7	0.525	8	0.6	8	0.6
Low Cost	0.1	$/Unit	4	0.4	5	0.5	6	0.6	7	0.7	9	0.9	8	0.8
Low Power Usage	0.05	Watts/Type	4	0.2	5	0.25	6	0.3	7	0.35	7	0.35	7	0.35
User Friendly Operation	0.015	Y/N	7	0.105	7	0.105	6	0.09	7	0.105	8	0.12	8	0.12
Environmental Protection	0.12	Y/N	9	1.08	8	0.96	5	0.6	5	0.6	3	0.36	5	0.6
Temp Reading Capability	0.015	Y/N	5	0.075	8	0.12	8	0.12	8	0.12	6	0.09	6	0.09
Rapid Deployment & Distribution	0.06	time to deploy	10	0.6	6	0.36	8	0.48	6	0.36	9	0.54	6	0.36
Fits cooling system, windows,	0.09	Y/N	5	0.45	7	0.63	6	0.54	6	0.54	4	0.36	7	0.63
Materials locally sourced	0.03	Y/N	9	0.27	6	0.18	7	0.21	6	0.18	9	0.27	8	0.24
Can be Manufactured in Ghana	0.06	Y/N	9	0.54	6	0.36	7	0.42	6	0.36	9	0.54	7	0.42
Non-intimidating Appearance	0.1	Y/N	9	0.9	6	0.6	7	0.7	6	0.6	7	0.7	7	0.7
Sample Testing Possible	0.01	Y/N	7	0.07	6	0.06	4	0.04	6	0.06	6	0.06	7	0.07
		Sum:		**7.015**		**6.575**		**6.425**		**6.525**		**6.415**		**6.555**

APPENDIX G: ENGINEERING DRAWINGS





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			CHECKED	DO	11/30/2020
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Acrylic	COMMENTS:		
NEXT ASSY	USED ON	FINISH Burr Free			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Front Acrylic Panel 1

SIZE	DWG. NO.	REV
A	2	

SCALE: 1:24 WEIGHT: SHEET 1 OF 1

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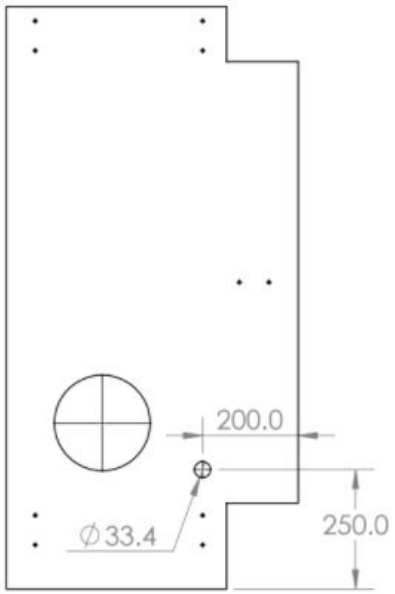

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.05	DRAWN	GM	11/29/2020
			CHECKED	DO	11/30/2020
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Acrylic	COMMENTS: DWG. NO. 2 shows placement of holes as well as diameters. This drawing shows the additional modifications to the Front Acrylic Panel 1. These two parts are meant to be similar.		
NEXT ASSY	USED ON	FINISH Burr Free			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Front Acrylic Panel 2

SIZE	DWG. NO.	REV
A	3	

SCALE: 1:20 WEIGHT: SHEET 1 OF 1

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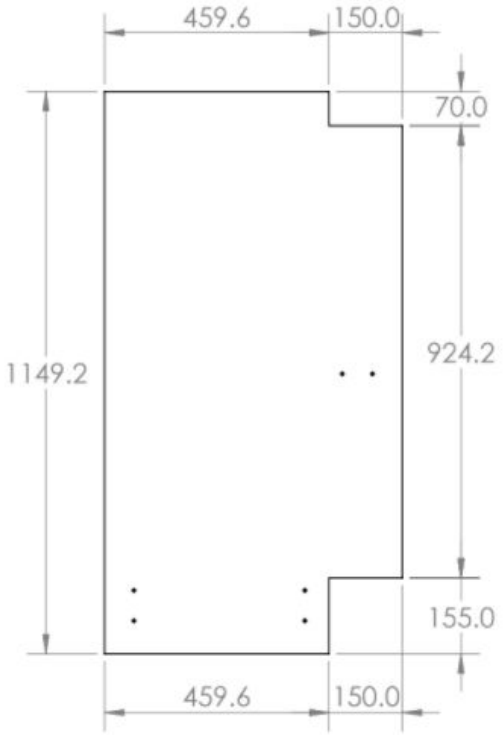

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			CHECKED	DO	11/30/2020
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Acrylic	COMMENTS: This drawing shows cutout for both roof panels.		
NEXT ASSY	USED ON	FINISH Burr Free			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Roof Acrylic Panel Cutout

SIZE	DWG. NO.	REV
A	4	

SCALE: 1:20 WEIGHT: SHEET 1 OF 1

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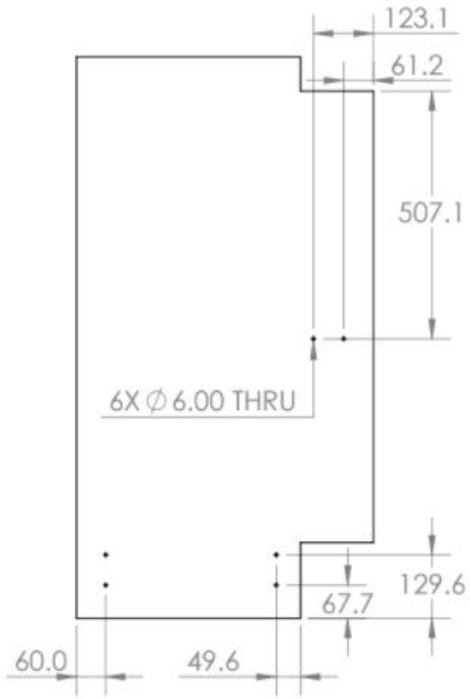

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± ONE PLACE DECIMAL ±.1 TWO PLACE DECIMAL ±.05	DRAWN	GM	11/29/2020
			CHECKED	DO	11/30/2020
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Acrylic	COMMENTS: This drawing is meant to be repeated twice for both roof panels. Dimensions and placement are the same for both panels.		
NEXT ASSY	USED ON	FINISH Burr Free			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Roof Acrylic Panel

SIZE	DWG. NO.	REV
A	5	
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

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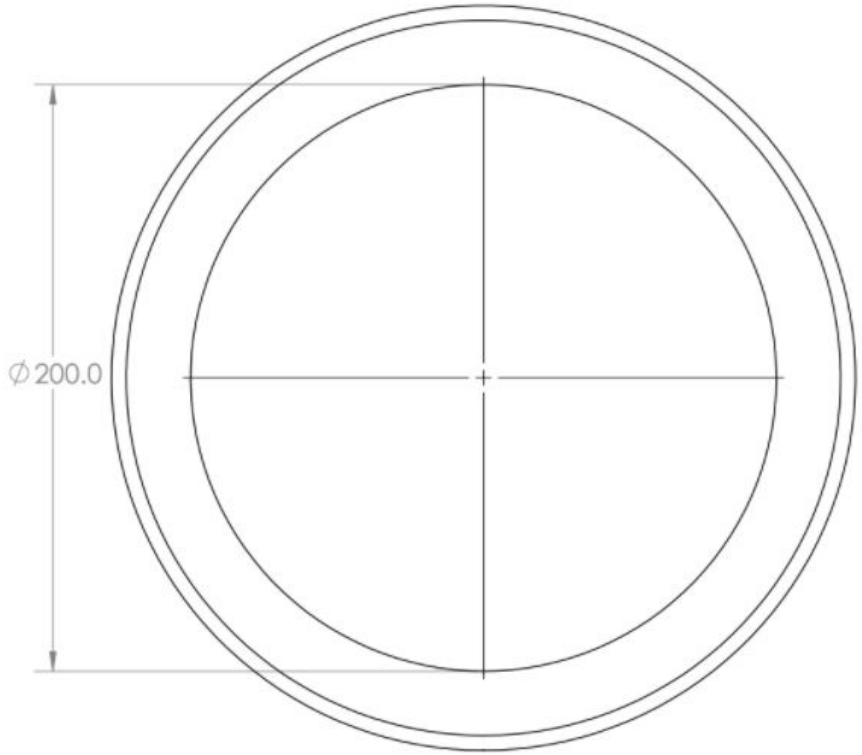

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
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			CHECKED	DO	11/30/2020
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL PVC	COMMENTS: This drawing is meant to be repeated twice for both armhole extensions. Circular cutout is made in the center of the PVC piece.		
NEXT ASSY	USED ON	FINISH Burr Free			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Armhole Extension

SIZE	DWG. NO.	REV
A	6	

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

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APPENDIX H: MANUFACTURING PLANS & ASSEMBLY INSTRUCTIONS

Manufacturing Plan

Notes	Steps	Process Description	Figure	Machine	Materials
Perform Pre-Setup 3 days before full construction to allow acrylic glue to dry	Pre-Setup	Machine acrylic panels to desired shape and install screw holes		Scoring knife & M6 size drill bit	D1 & D2
		Glue 1st set of acrylic panels together using Weld-On Acrylic Adhesive	H.1	N/A	D1 & D2 A
		Install armhole holders into holes in front panel using Acrylic Adhesive		N/A	Q1 & Q2
		Glue 2nd set of acrylic panels together using Weld-On Acrylic Adhesive	H.2	N/A	D3 & D4 A
Throughout this assembly, use a rubber hammer to ensure that PVC connections are tight	1	Connect 2 PVC pipes to 2 separate 3-Way PVC Connectors	H.3	N/A	B1 & B2 E1 & E2
	2	Connect two 4-way PVC connectors to each end of another PVC pipe. Connect elbow spigots to the opposite ends of the two 4-way PVC	H.4	N/A	B3 F1 & F2 G1 & G2

		connectors			
	3	Attach assembly from Step 1 to elbow spigots in assembly from Step 2	H.5	N/A	B1, B2, & B3 E1 & E2 F1 & F2 G1 & G2
	4	Repeat Step 1 with a 2nd set of PVC pipes and 3-Way PVC Connectors	H.6	N/A	B4 & B5 E3 & E4
	5	Repeat Step 2 with a 2nd set of 4-Way PVC Connectors, elbow spigots, and a PVC pipe	H.7	N/A	B6 F3 & F4 G3 & G4
	6	Repeat Step 3 by attaching the assembly from Step 4 to the elbow spigots in the assembly from Step 5	H.8	N/A	B4 & B5 G3 & G4
	7	Attach PVC pipes to the corresponding hole on the 4-Way connection from Step 6 as shown in Figure H.9	H.9	N/A	B7 & B8 F3 & F4
	8	Attach assembly from Step 7 to assembly from Step 3 as shown in Figure H.10	H.10	N/A	B7 & B8 F1 & F2
	9	Attach 4 PVC pies to the corresponding holes on the 4-Way PVC Connections on the assembly from Step 8	H.11	N/A	B9, B10, B11, & B12 F1, F2, F3, & F4

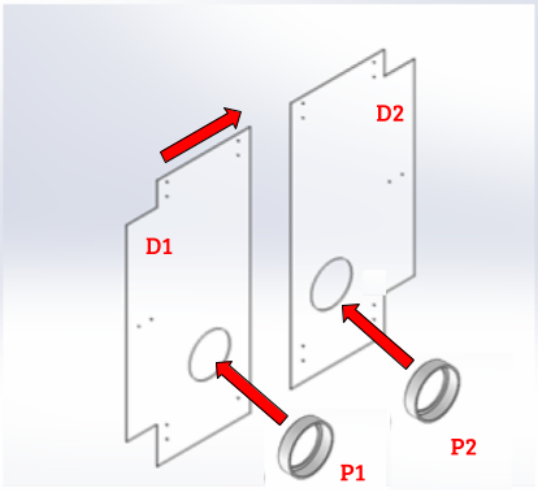
	10	Attach 6 different U-Brackets to the set of screws as shown in the red circles in Figure H.12. Make sure the orientation of the acrylic panels matches the image. The screws are tightened as shown in Figure H.13	H.12, H.13	N/A	D1 & D2 H1, N1, N2, I1, & M1 H2, N3, N4, I2, & M2 H3, N5, N6, I3, & M3 H4, N7, N8, I4, & M4 H5, N9, N10, I5, & M5 H6, N11, N12, I6, & M6
	11	Slide a PVC pipe through the U-Brackets as shown in Figure H.14. Then attach two 4-Way Connectors at either end of the pipe.	H.14	N/A	B13 F5 & F6
	12	Attach 3-Way Connectors at the end of a new PVC pipe as shown on the top half of Figure H.15. Then attach 2 vertical PVC pipes into the corresponding holes of the 3-Way connections. Slide the vertical PVC pipes into the remaining U-Brackets as shown. Attach the assembly into the 4-Way PVC Connections from Step 11 shown in the red boxes.	H.15	N/A	B14, B15, & B16 E5 & E6 F5 & F6
	13	Attach U-Brackets to the set of screw holes on panels D3 & D4 as shown in Figure H.16. Use	H.16	N/A	D3 & D4 H7, N13, N14, I7, & M7 H8, N15, N16, I8, & M8

		the same fixation process as in Step 10			
	14	Slide vertical PVC pipes through the U-Brackets from Step 13	H.17	N/A	B17 & B18 H7 & H8
	15	Attach 3-Way Connectors at the end of a new PVC pipe as shown on the top half of Figure H.15. Then attach the2 vertical PVC pipes from Step 14 into the corresponding holes of the 3-Way connections.	H.18	N/A	B17 & B18 E8 & E7
	16	Attach PVC pipes into the remaining holes of the three-way connection from STEP 15.	H.19	N/A	B20 & B21 E7 & E8
	17	Attach 4-Way connections at the bottom of PVC pipes from STEP 16. Make sure the four-way connection has the same orientation as Figure H.20	H.20	N/A	B20 & B21 F7 & F8
	18	Attach new PVC pipes to the corresponding holes of the 4-Way connections from Step 17.	H.21	N/A	B23 & B22 F7 & F8

	19	Attach subassembly from Step 18 to subassembly from Step 12 (PVC pipes to the three and four way connectors). The flat roof acrylic panel should be in line with the three-way connectors. Make sure the orientation matches that shown in Figure H.22.	H.22	N/A	B17, B19, B22, & B23 E5, E6, F5, & F6
	20	Attach U-Brackets, using the same U-Bracket fixation process mentioned earlier, on the remaining set of screw holes on the roof acrylic panel.	H.23	N/A	H9, N17. N18, I9, & M9 H10, N19, N20, I10, & M10 H11, N21, N22, I11, & M11 H12, N23, N24, I12, & M12
	21	Attach the subassembly from the previous step at the four-way connectors to the subassembly from Step 9 at the vertical PVC components.	H.24	N/A	B9, B10, B11, B12 F5, F6, F7, & F8

Assembly Instructions

PRE-SETUP

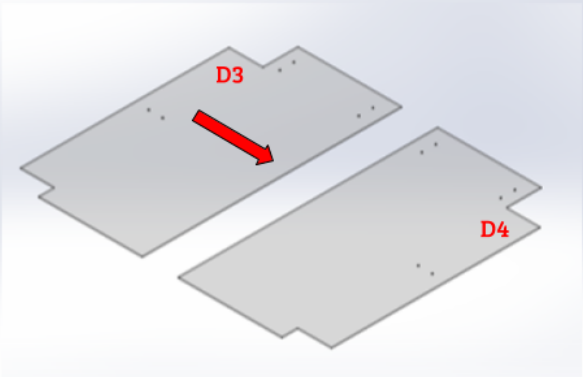


Notes

The acrylic panels shown are glued together accordingly. Additionally, armhole extension are attached as shown. Make sure orientation matches the image and surfaces of the armhole extensions are flush with the acrylic panels. This should be done three days before assembly to allow acrylic glue to dry.

Figure H.1

PRE-SETUP

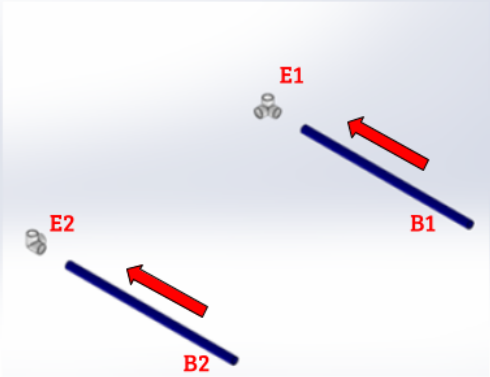


Notes

The acrylic panels shown are glued together accordingly. This should be done three days before assembly to allow acrylic glue to dry.

Figure H.2

STEP 1



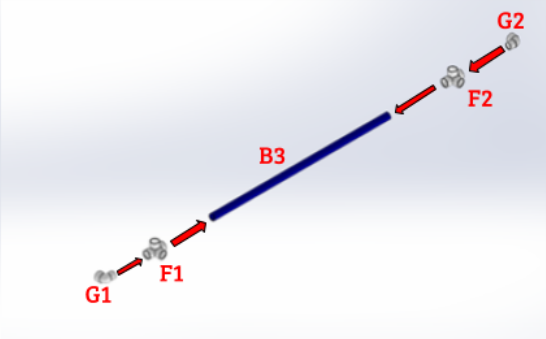
Notes

PVC pipe are connected to 3-Way PVC Connections. The color of the PVC pipe does not matter. The following assembly steps show blue and white PVC pipes. Blue PVC pipes show pipes in the horizontal direction and white PVC pipes show pipes in the vertical direction to make visuals easier to understand.

*To ensure PVC connections are tight, use rubber hammer to attach components throughout this assembly.

Figure H.3

STEP 2



Notes

PVC Pipe is connected to 4-Way PVC connections on both ends with the following orientation. Afterwards, elbow spigots are attached to both ends.

Figure H.4

STEP 3

Notes

The outcome of **STEP 1** is attached to the elbow spigots from **STEP 2**.

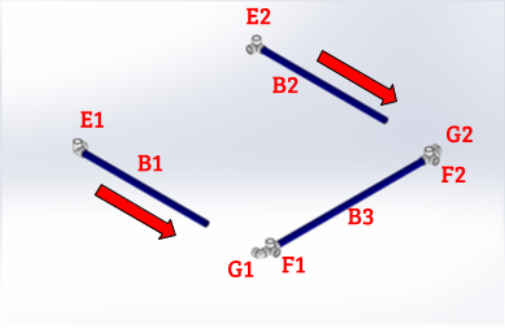


Figure H.5

STEP 4

Notes

Follow same process as **STEP 1**.

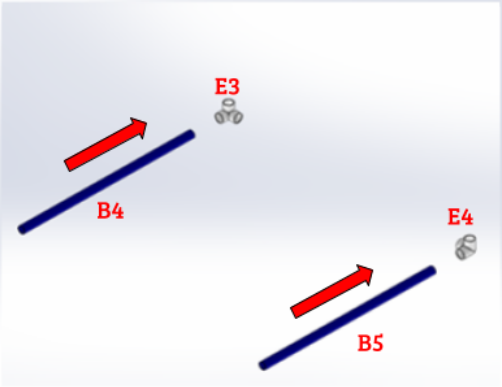


Figure H.6

STEP 5

Notes

Follow the same process as **STEP 2**.

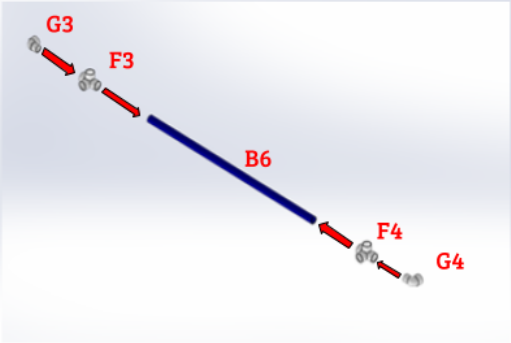


Figure H.7

STEP 6

Notes

Follow same process as **STEP 3**.

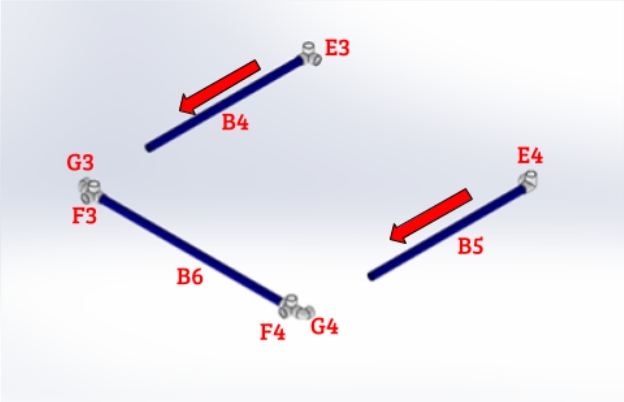


Figure H.8

STEP 7

Notes

Attach PVC pipes to the corresponding hole on the 4-Way connection from **STEP 6**.

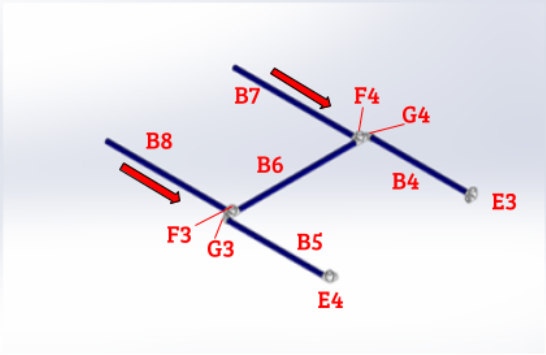


Figure H.9

STEP 8

Notes

Attach assembly from **STEP 7** to assembly from **STEP 3** as shown.

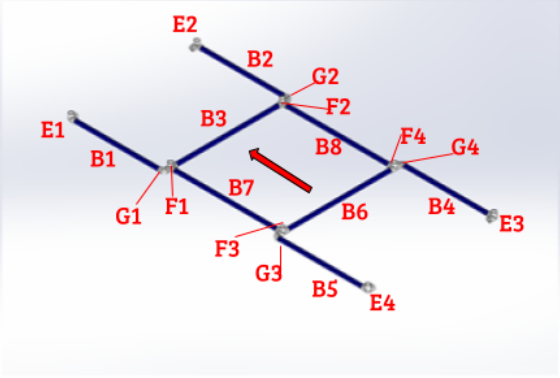


Figure H.10

STEP 9

Notes

Attach PVC pipes to the corresponding hole on the 4-Way Connection from **STEP 8**.

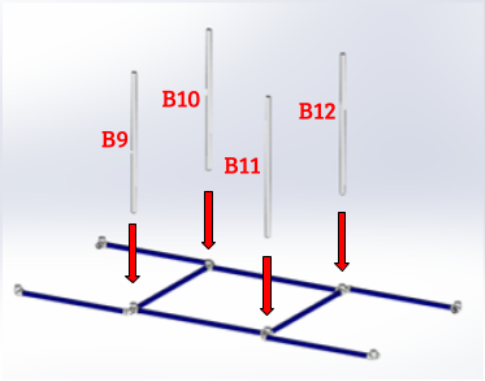


Figure H.11

STEP 10

Notes

Attach U-Brackets to the following set of screws as shown in the red circles. Make sure orientation of the acrylic panels matches the image. U-Bracket fixation process is shown on the next slide.

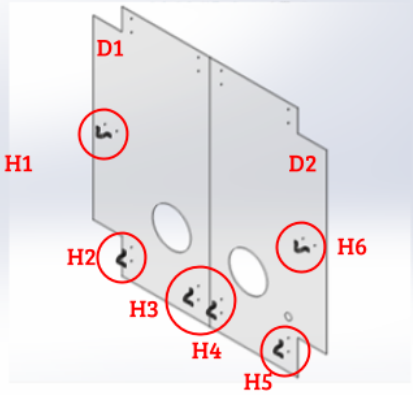


Figure H.12

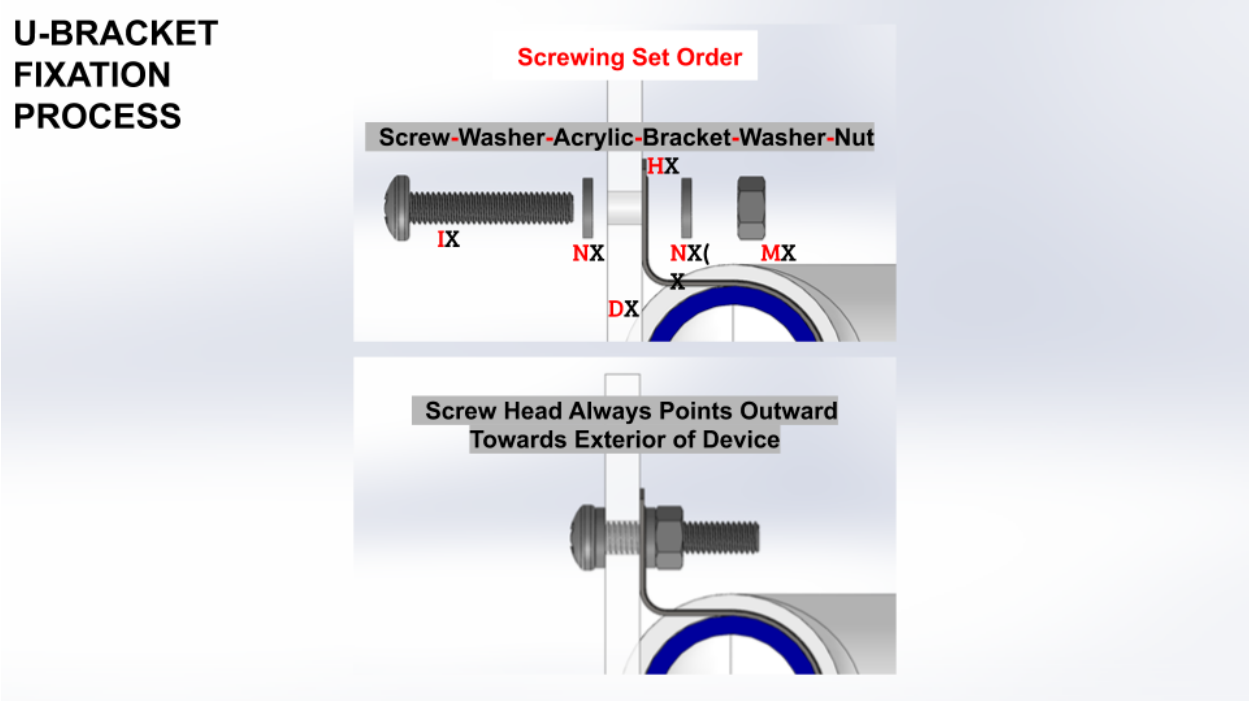


Figure H.13

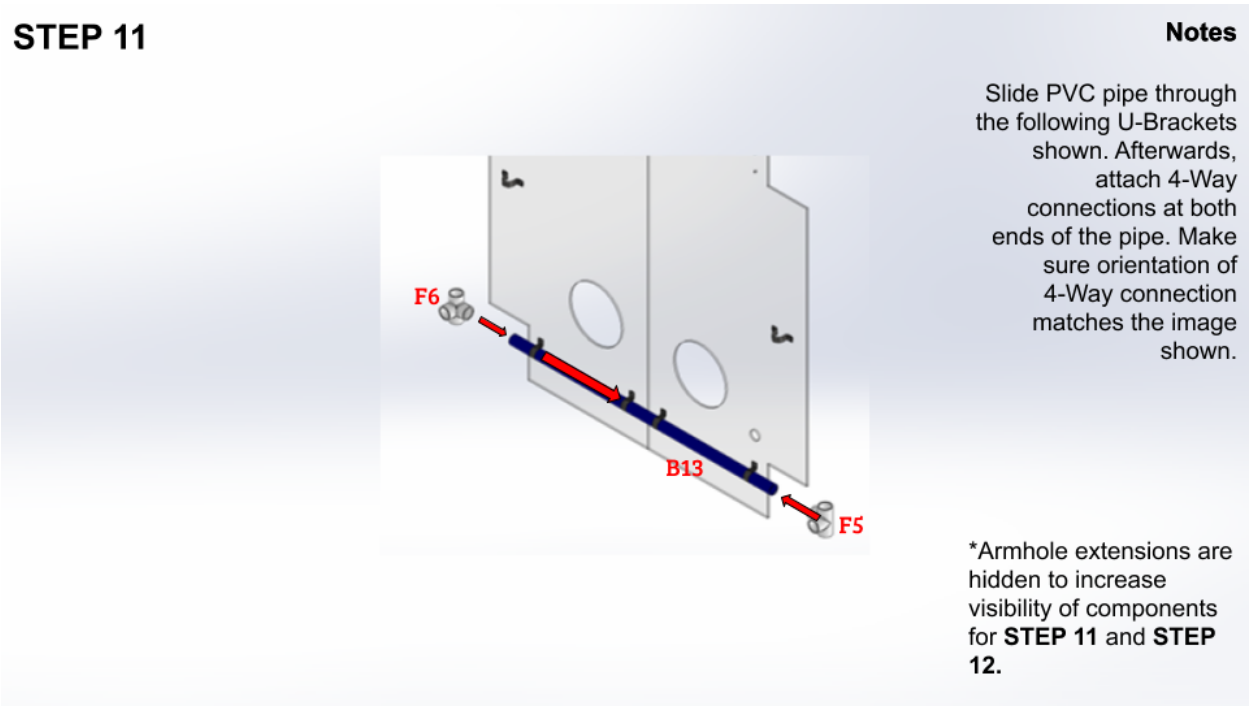
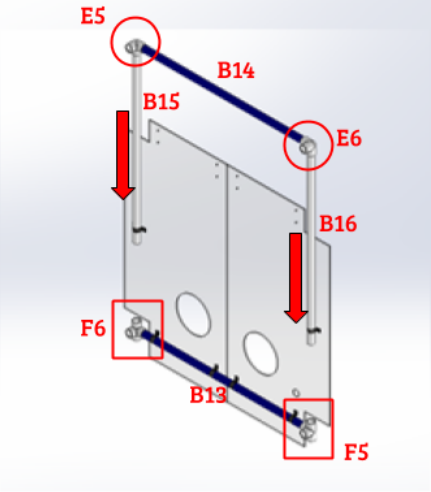


Figure H.14

STEP 12

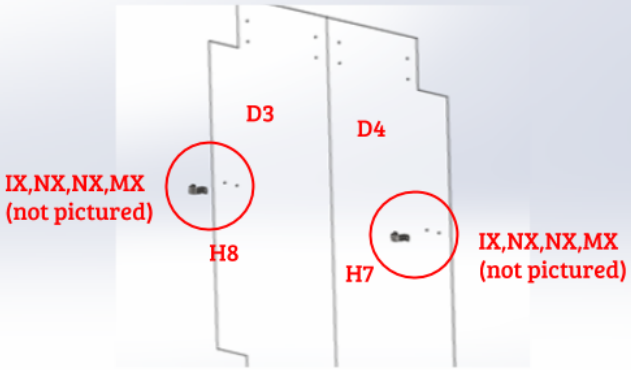


Notes

Attach 3-Way connections, shown in red circles, at the end of a different pipe as shown on the top section of the image. Make sure orientation matches the image. Afterwards, attach PVC pipes into the corresponding hole of the 3-Way connections. Then, slide the vertical pipes into the remaining U-Brackets as shown. Attach this subassembly into the 4-Way connection from **STEP 11** shown in red boxes. Make sure orientation of the 4-Way connections matches.

Figure H.15

STEP 13



Notes

Attach U-Brackets to the following set of screw holes. Use the same **U-Bracket fixation process** previously mentioned.

Figure H.16

STEP 14

Notes

Slide PVC Pipes through the U-Brackets from **STEP 13**.

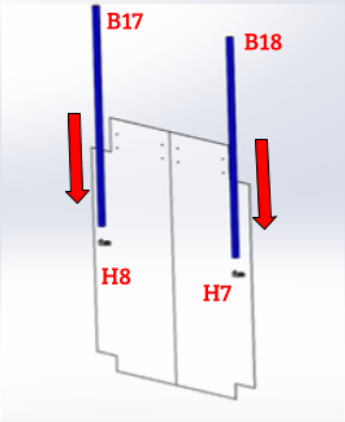


Figure H.17

STEP 15

Notes

Attach 3-Way connections, shown in red circles, at the end of a different pipe as shown on the top section of the image. Make sure orientation matches the image. Afterwards, attach this subassby to the PVC pipes from **STEP 14**. Make sure orientation of acrylic panels match the image.

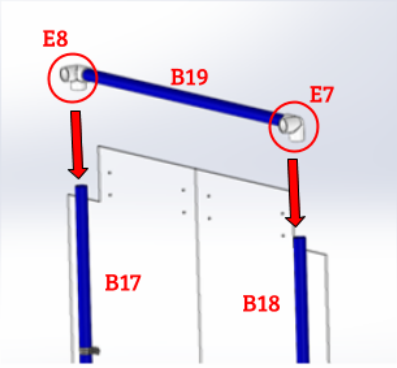


Figure H.18

STEP 16

Notes

Attach PVC pipes into the remaining hole of the 3-Way connection from **STEP 15**.

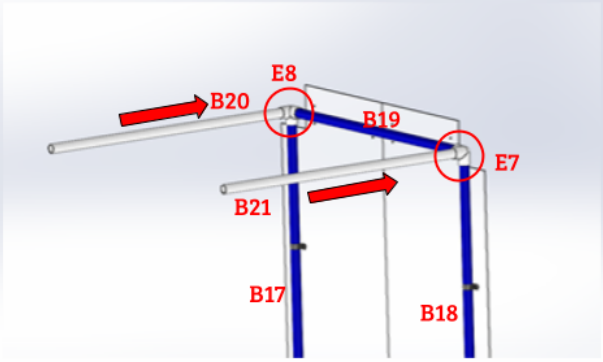


Figure H.19

STEP 17

Notes

Attach 4-Way connections at the bottom of PVC pipes from **STEP 16**. Make sure 4-Way connection has the same orientation as the image shown.

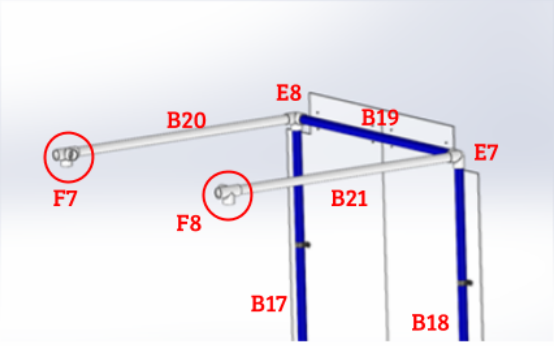


Figure H.20

STEP 18

Notes

Attach PVC pipes to the corresponding hole of the 4-Way connections from **STEP 17**.

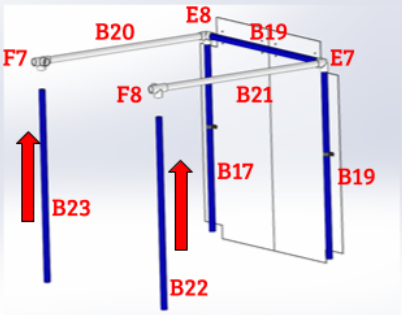


Figure H.21

STEP 19

Notes

Attach subassembly from **STEP 18** to subassembly from **STEP 12**. Make sure orientation of subassemblies match the image.

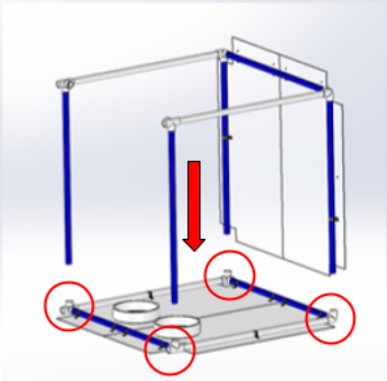


Figure H.22

STEP 20

Notes

Attach U-Brackets, using the same U-Bracket fixation process mentioned, on the remaining set of screw holes as shown in the image.

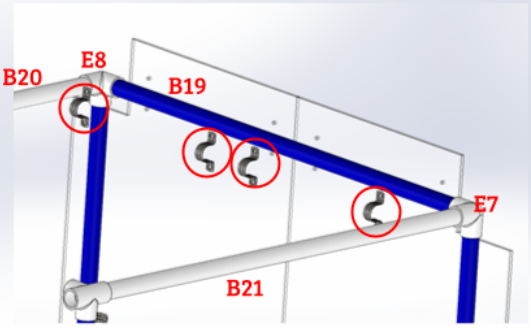


Figure H.23

STEP 21

Notes

Attach subassembly from **STEP 20** to subassembly from **STEP 9**. Make sure orientation of subassemblies match the image on the following slide.

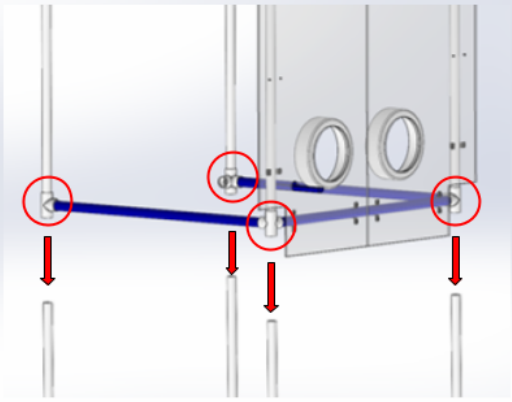


Figure H.24

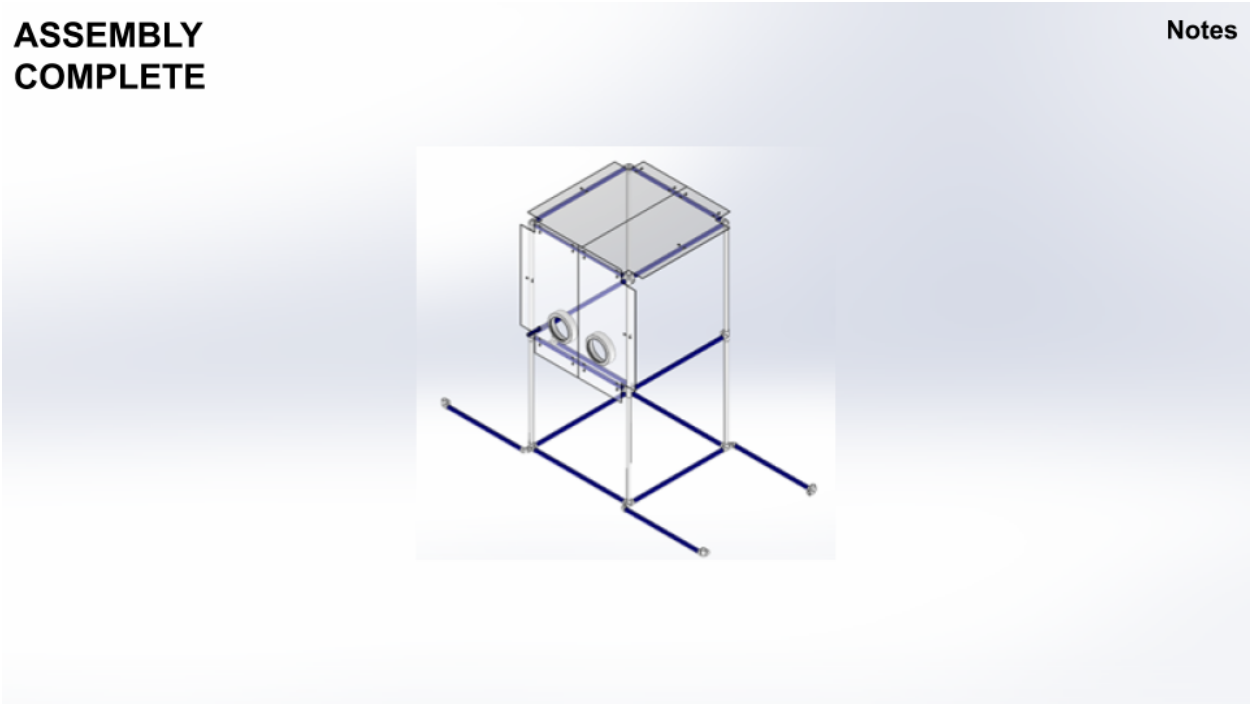
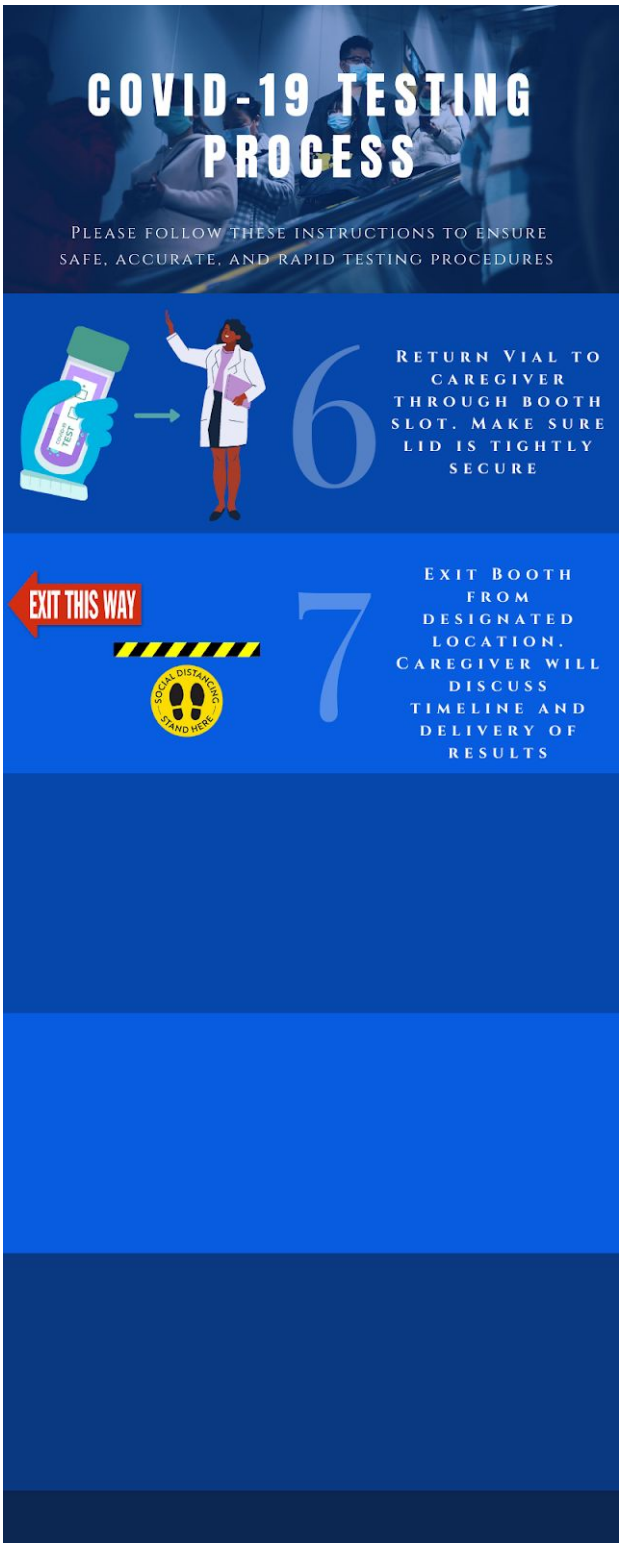


Figure H.25

APPENDIX I: USER PROTOCOL POSTER



APPENDIX J: CAREGIVER PROTOCOL

1. Before entering the booth, the caregiver should prepare a spray bottle of 10-13% diluted bleach solution (by volume) by mixing bleach and water together. A second spray bottle filled with water should be prepared.
2. The caregiver should place the spray bottles and a towel on the table outside of the booth within reach of the gloves
3. The caregiver should enter the booth and place their hands into the gloves
4. When a new patient approaches the booth, the caregiver should tell the patient to stop at the indicated line and point them to the posters with patient testing instructions
5. The caregiver should record the patient's personal information, including their address, contact information, and recent symptoms on a sheet inside the booth.
6. The caregiver should use the non-contact thermometer to read the patient's temperature and record the information on the sheet.
7. The caregiver should take a clean saliva sample vial and label it so that it can be tracked back to the patient
8. The caregiver should hand the vial to the patient for the patient to spit into.
9. The caregiver should take the vial back from the patient and place it into the icebox for storage
10. The caregiver should direct the current patient to the exit and prepare for the next patient.
11. Between each new patient the caregiver should spray the bleach solution on the gloves and "wash" the gloves from inside the booth. The caregiver should "wash" their gloves for 30 seconds [1]
12. They should then spray the gloves with water from the other spray bottle and rub their hands dry using the towel

APPENDIX K: MATERIALS USED WITHIN EDUPACK

Qty.	Component name	Material	Recycled content	Mass (lb)	Primary process	Length (ft)	Secondary process	% removed	End of life	% recovered
2	PVC Pipe	PVC (rigid, molding an...	Virgin (0%)	10.68	Polymer extrusion	32.81		0	Landfill	100
1	Acrylic Adhesive	MABS (transparent AB...	Virgin (0%)	0.25	Polymer molding	Not Required		0	Landfill	100
1	PVC Cement	MABS (transparent AB...	Virgin (0%)	1	Polymer molding	Not Required		0	Landfill	100
4	Acrylic Sheet	PMMA (cast sheet)	Virgin (0%)	12.38	Polymer extrusion	4		0	Landfill	100
1	U Bracket	Stainless steel, ferritic,...	Virgin (0%)	0.925	Casting	Not Required		0	Landfill	100
1	Wheels	PUR(r) (casting resin, u...	Virgin (0%)	2.88	Polymer molding	Not Required		0	Landfill	100
1	Tarp	PE-LD (molding and e...	Virgin (0%)	1.39	Polymer extrusion	10		0	Landfill	100
1	Screws	Stainless steel, ferritic,...	Virgin (0%)	0.3875	Casting	Not Required		0	Landfill	100
1	Plastic Bin	PUR(r) (casting resin, u...	Virgin (0%)	0.9	Polymer molding	Not Required		0	Landfill	100
1	Nuts/Washers	Stainless steel, ferritic,...	Virgin (0%)	0.2488	Casting	Not Required		0	Landfill	100

APPENDIX L: ENGINEERING STANDARDS

Standards are tools that can be used during the problem definition,solution development, and verification stages of engineering projects. They specifically help ensure quality, reliability, and safety for specific engineering applications and products. Standards also serve as guidelines for engineers to adhere to with components or equipment. During the requirements and specification phase of the project, our team spent time researching relevant engineering standards to define our specifications in a quantifiable and measurable way. Our team leveraged these for requirements relating to personal protective equipment quality, viral particle protection, environmental protection, and sound isolation.

A list of the official standards used in this project is shown below:

- EN 455, EN 374, ANSI/ISEA 105-2011, ASTM D6319-10 or equivalent
    - The following standards were recommended by the Ghana Health Service for examination gloves and hand protection. We utilized these standards when constructing our bill of materials by choosing an appropriate glove model that fulfilled these particular standards and requirements for viral and contact-based protection against COVID-19.

1. Specifically, EN 455 is a standard for ensuring gloves are safe from bodily fluids, chemicals, bacteria and also prevent infection on the surfaces they contact (like patients). Testing this standard involves ensuring physical resistance to tearing, breaking, or chemical leakage. This is important, as we do not want to increase transmission risk to either our caregiver or patient. EN 374 similarly refers to standards that make sure gloves are resistant against chemicals or micro-organisms (permeation, degradation, or general contact).

2. ANSI/ISEA 105 standards are specific to hand protection for performance properties related to mechanical protection (cut-resistance, puncture resistance and abrasion resistance), chemical protection (permeation resistance, degradation) and other performance characteristics such as ignition resistance and vibration reductions. This is also important to ensure our testing booth gloves can last for their intended duration and remain secured within hose clamps, while being able to endure any forces that may cause cuts/punctures.

3. Lastly, the ASTM D6319-10 standard is specific to nitrile rubber gloves used in medical examinations. This ensures gloves are powder-free (as these can present an allergic risk to some patients and caregivers), of appropriate thickness and length, have high tensile strength for greater durability and dexterity, and have a

high level of elongation. This again ensures our gloves are resistant to deterioration and pose fewer allergic risks to caregivers making use of them.

- STC-35 (Sound Transmission Class)
    - An STC-35 rating (as described in our verification section) means that, with respect to sound transmission class, a wall reduces the transmission of sound to its opposite side by 35 dB. The standard also ensures normal speech can be heard within a short distance from the wall or enclosure being tested, while speech is unintelligible when standing more than a few meters away from the booth. Our team chose to use this standard because STC classes are frequently used in industry for soundproof control rooms or acoustic enclosures as an unbiased and numerical test method for sound transmission [63]. A rigorous method such as this one will also ensure that sensitive patient information cannot be overheard by anyone other than the patient currently being tested at the booth, which ensures that patient privacy is respected.

- IP55 standard (EN 60529)
    - The EN 60529 standard determines the ability of an enclosure to protect its contents from contaminants. Ingress Protection (IP) is a subset of this standard specific to dust and water protection. Our team used this to develop a quantifiable way to evaluate if our solution could be dust-proof or water-proof, which was a desired requirement from our stakeholders. Specifically, IP 55 ratings are included in the specifications we outlined for Environmental Protection in our Reqs/Specs. The standards state that our booth must offer protection from total dust ingress (infiltration) and particles of 0.1- 1 mm size along with protection against low-pressure jets (6.3 mm) of directed water from any angle (limited ingress permitted with no harmful effects).

By using these standards we were able to establish quantitative guidelines for our device's operation. This allowed us to construct our booth's design more quickly since we knew what requirements we had to achieve.

APPENDIX M: ENGINEERING INCLUSIVITY

Team 14 incorporated inclusive design when interacting with stakeholders, defining the problem, and making design decisions. Social identity and power had a part in the design process for the team.

Team 14 experienced many situations where visible power came into play. The team developed a COVID-19 testing booth for low-resource areas in Ghana and the goal was to limit disposable PPE while still providing viral transmission protection. Certain components of the testing booth such as hand protection, sample storage, the amount of environmental protection, and its temperature reading capability were required to comply with many standards used by the Ghanain federal government and Ghana Health Service. This was done so that the device would be effective and usable by civilians. The direct power over the standards of sample storage caused the device cost to rise, affecting the team's design possibilities. The team's design possibilities became more limited as one of the requirements for the device was that the device be low-cost and, since the sample storage that suited the standards is so costly, it gave the team a smaller budget. This affected the materials used when creating the booth.

Social identities of the team had an effect on the initial analysis and definition of the problem. During concept development, the team's initial thought was to have the patients write down their information in order to communicate it with the caregiver. However, it was brought to our attention by our Ghanaian sponsors that it would be more user-friendly to have the patients communicate their information vocally because of issues with literacy. This was not apparent to the team because our social identities were centered around being college-educated students. To make the design process more inclusive the team could have conducted surveys with Ghanain citizens and healthcare workers on certain design characteristics to get a wider range of input from people with different social identities.

Team 14 made design decisions using invited spaces. During the concept development process the team put together design questions for their colleagues to address and received feedback on different design concepts that could address and solve the team's problem. The team also met with stakeholders intermittently throughout the course of the project, bringing new ideas and further-developed design concepts in search of feedback and things to improve. It was important that the team considered stakeholder input because their social identities were more relevant to evaluating the usability of the device. The team also found that they had a certain amount of hidden social power, since they were the ones who decided to approach the stakeholders for feedback. This meant that the team could have limited the stakeholders' input and influence over the design process. In other words, it was ultimately up to the team to decide whose input to gather and how to apply each stakeholders' insights. However, the team recognized the value in receiving direct stakeholder feedback since they realized that different social identities that were valuable to the development of the project design.

APPENDIX N: ENVIRONMENTAL CONTEXT ASSESSMENT

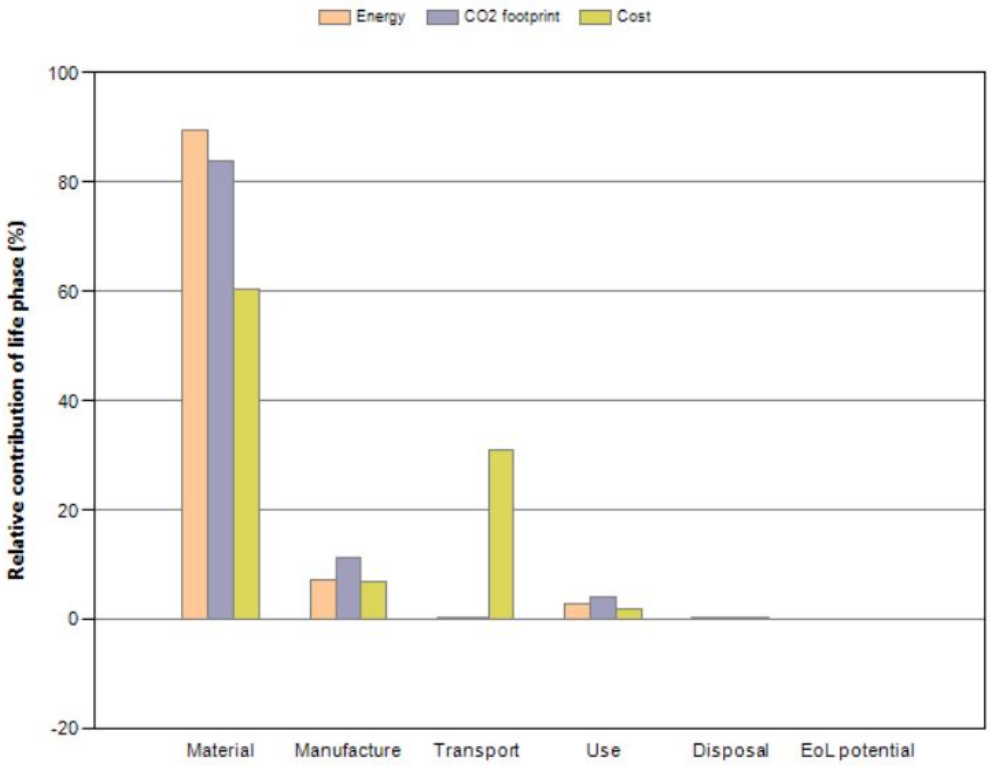
As stated earlier in the report, COVID-19 is a pandemic that has had a critical impact around the world. However, its effects have the potential to do the most damage in countries with still-developing infrastructure and support systems such as Ghana[9]. Since a vaccine for COVID-19 has not yet been developed, the current solution to stopping the spread of the virus is to quarantine affected individuals. However, in order to do this, countries must have a way of testing their citizens to determine which individuals are infected. Due to the difficulties present in producing a cost-effective testing solution, many cities within Ghana are still attempting to find ways to decrease the spread of the virus. As of November 8th, Ghana has experienced 52,274 cases of COVID-19. As described above, a recent study showed that current practices in Accra, Ghana have led to the exposure of more than a million people to COVID-19[10]. The study found that the exposure rate was highest in people who tested in low-income places such as markets and lory stations, as opposed to those who tested at malls. This shows that there is a societal need for a low-cost testing solution that can be implemented in low-income neighborhoods across Ghana.

Given that our system allows caregivers and patients to safely interact during sample collection and that the cost of the system remains below the limits established by our stakeholders, we are able to say that our system makes significant progress towards an unmet and important societal challenge.

There is little to no potential for the system to lead to undesirable consequences in its lifecycle that overshadow its societal benefits. Since February, there have been 325 deaths due to COVID-19 within Ghana. While this number is much smaller than it is in some countries,such as the United States, it still represents a significant value. To that end, the device that we have developed would have to do significant damage to the environment or to society to overshadow its benefits. However, as can be seen from Figures N.1, N.2, and N.3, which were produced through an eco-audit, the device does minimal damage to the environment throughout its lifetime. A single unit consumes approximately $8.36 * 10^5$ kJ/year. While this number may seem large it should be noted that the largest amount of energy is consumed during the sourcing of the raw materials, which will only occur once during the device's lifetime. In comparison the device requires very little energy to be manufactured or used. Given that the device uses no energy to power itself, the only energy expended over its lifetime after production is the energy used to transfer the device to the testing sites.

In terms of its carbon footprint, we found that the device would introduce 378 lbs of CO_2 per year. For comparison, the average car produces ~9400 lbs of CO_2 per year [66]. Additionally, similar to the energy, the largest portion of the CO_2 footprint comes from the material sourcing which only occurs once during the device's lifetime. Using these metrics, we can say that there

is little potential for the system to lead to undesirable consequences that will overshadow its benefits.

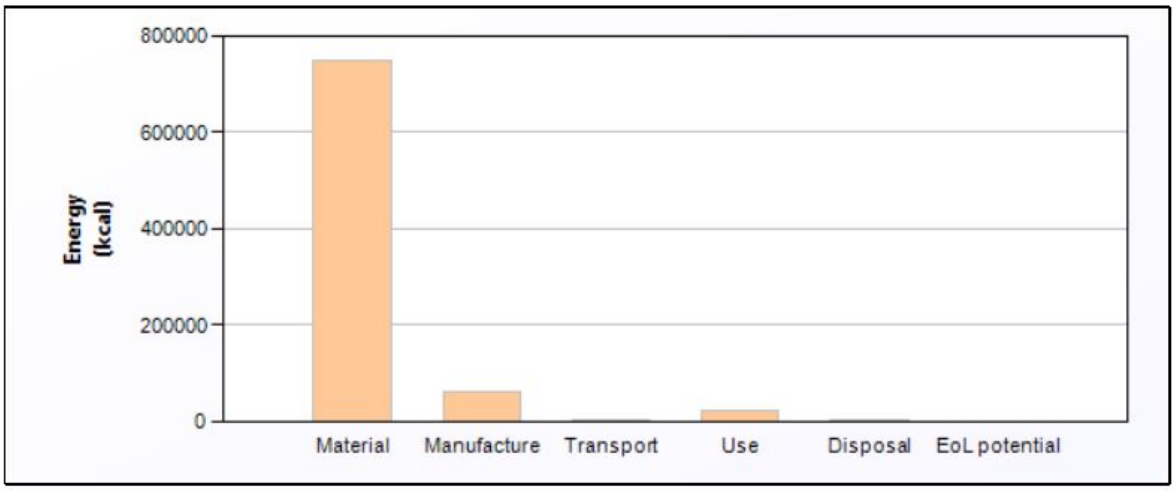


Phase	Energy (kcal)	Energy (%)	CO2 footprint (lb)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	7.47e+05	89.4	317	83.8	83.7	60.3
Manufacture	6.14e+04	7.4	43	11.4	9.39	6.77
Transport	2.25e+03	0.3	1.49	0.4	42.9	30.9
Use	2.34e+04	2.8	15.5	4.1	2.59	1.87
Disposal	1.71e+03	0.2	1.1	0.3	0.23	0.165
Total (for first life)	**8.36e+05**	**100**	**378**	**100**	**139**	**100**
End of life potential	0		0			

Testing Booth.prd NOTE: Differences of less than 20% are not usually significant. Page 1 / 4

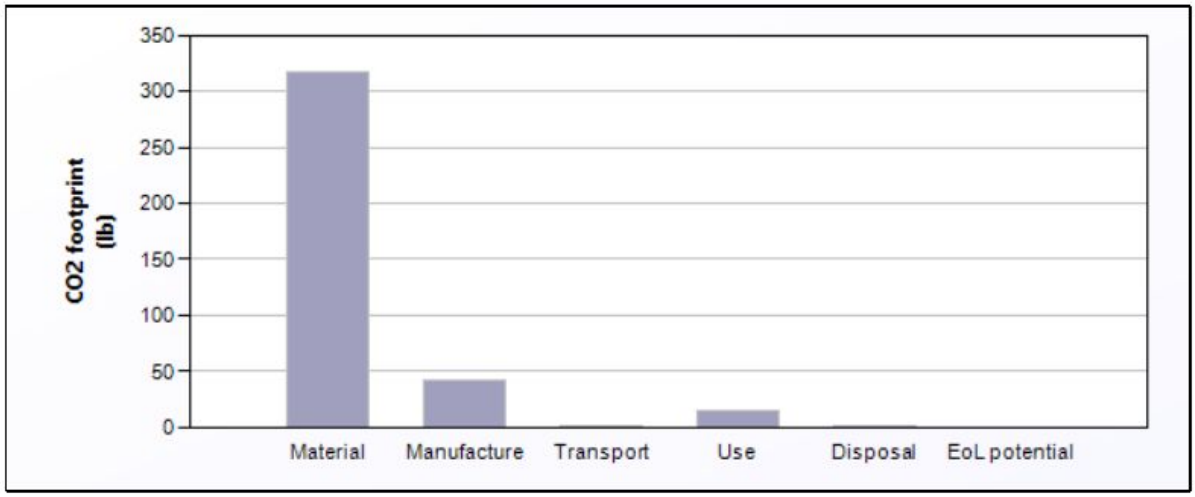
See notes on precision and data sources. Tuesday, December 8, 2020

Figure N.1: Summary of Lifecycle Cost



	Energy (kcal/year)
Equivalent annual environmental burden (averaged over 1 year product life):	8.36e+05

Figure N.2: Energy Burden Over 1 Year of Product Life



	CO2 (lb/year)
Equivalent annual environmental burden (averaged over 1 year product life):	378

Figure N.3: CO_2 Burden Over 1 Year of Product Life

APPENDIX O: SOCIAL CONTEXT ASSESSMENT

It is very likely that the device, or some future version of the device, will be adopted and self-sustaining in the market. While the world is closer to having a publicly-available vaccine for the coronavirus, that does not obviate the need for testing. Since a vaccine would only decrease the chances that people would contract COVID-19, testing must still be conducted to ensure that people are truly not infected and are not simply asymptomatic. Specifically in Ghana, the need for testing has only risen since the advent of the virus. Based on the information provided, in the COVID-19 Background section above, that stated that more than one million people have been exposed to COVID-19 in Accra, Ghana alone, it is clear that there is an unmet need for low-cost testing in Ghana. Our sponsors have informed us that there is a niche available for our product within the Ghanian market. While other testing solutions do exist and are currently being used in Ghana, they are expensive and cannot serve many of the lower-income communities within the country.

Using the cost analysis performed above in Figure 29, it is apparent that the highest proportion of the device's lifecycle cost comes from the sourcing of its materials and the transport of those materials. Since these events only occur once in the device's lifetime, the overall cost will not change much from the device's purchasing cost. In fact, the only significant cost incurred during the device's lifetime, outside of its initial purchase, is the cost of the gas required to transport the booth around the city. Given that the device only needs to be transported twice a day, this cost is minimal. Looking at the purchasing cost of the device, we found that it would cost ~$792.91. This is less than the $853.00 guideline established by our stakeholders. At this price, nearly all hospitals and communities around Ghana would be able to adopt the system. Additionally, given the low price, it is highly unlikely that the system will achieve such a high level of economic success that social systems in Ghana will be worse off. The entire purpose of the device is to save lives by preventing the spread of COVID-19 during the pandemic's early year(s). After the goal is accomplished, the devices will eventually be put out of use since the tests can be conducted at previously established facilities, like hospitals which are currently overloaded.

The technology is also quite resilient to disruptions in business as usual, since its entire purpose is to address a unique event. The entire pandemic can be thought of as a disruption in business as usual. By adapting our device to serve people during this time, we have created a system that will be able to work during similar times of turmoil and disruption. The testing booth is specifically designed to operate under pandemic conditions and since those conditions are much more stringent than normal conditions, the booth should also be capable of being used in other tasks that require the minimization of PPE usage. For example, our device could be adapted for use in situations like clinical studies and biohazard work, where care workers must interact with multiple people without wasting PPE.

APPENDIX P: ETHICAL DECISION MAKING

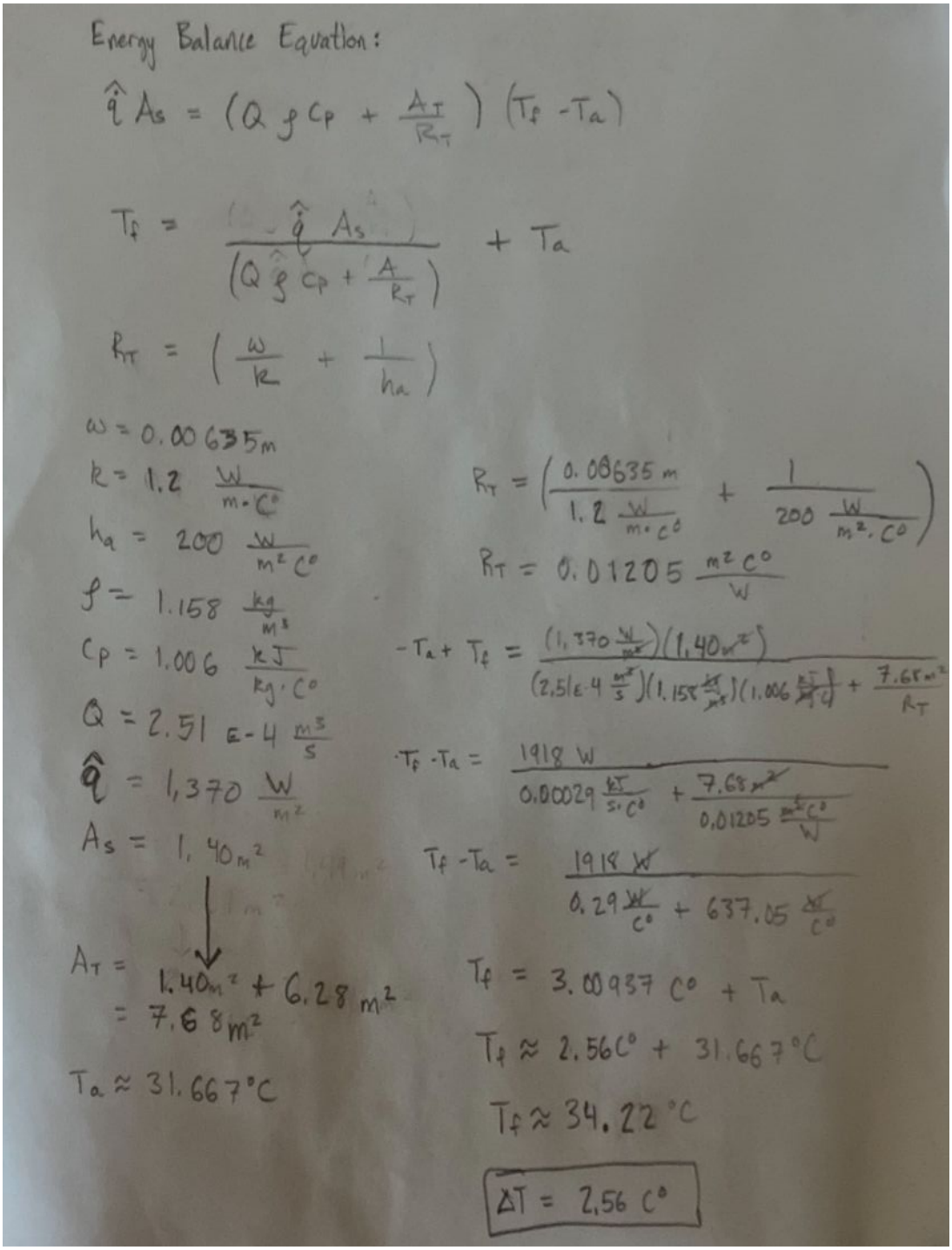
Team 14 kept in mind ethical decisions when creating the project. This mindset was a product of ASME's Code of Ethics of Engineers[67] and the ME 450 curriculum. The team followed the fundamental principles engineers should uphold in their engineering profession.

Team 14 used their skills and knowledge for the enhancement of human welfare by creating a device that protects healthcare workers and patients from transmitting COVID-19 during saliva tests. The team's device also has infographics that have figures and written instructions on the device. This is meant for the public who may be illiterate. This helps ensure that everyone has the same set of instructions and helps prevent transmission when getting tested. This device also has a lower cost compared to other benchmarks that have similar transmission protection. The intent of the design is not to make a profit, but rather to help and protect people who may not be able to access safe testing sites due to financial constraints.

Team 14 was also honest and impartial with their stakeholders and other professionals during the semester. The team did not want to provide any false information to stakeholders because this device could mean the difference between life and death for many communities. The team values the importance of the project and included all prioritized requirements the stakeholders asked for to ensure people are safe. The team does not have much knowledge of Ghanaian necessities, so it is important to ensure there is nothing lost in translation when speaking to stakeholders. The team made sure to update and improve the device along the way as communication with stakeholders increased. This process did include more work, but it was important to be honest and humble with our stakeholders to settle any difference which could save lives.

Moreover, Team 14 strived to increase the importance and merit of their engineering profession. Team 14 created a low resource device that may be able to compete with advanced medical booths that cost a lot more. Although the majority of the world seeks technological advancements, especially in the medical field, it is important to include a simpler, user-friendly low resource option to ensure that everyone has access to medical technology. Second and third-world countries might not be able to afford testing booth benchmarks mentioned previously. Team 14 sought after a low resource device that gives these countries an opportunity to invest in testing booth devices. Additionally, the team also encourages others to use and improve the team's device, if necessary. It is important to share results and improve technology based on those findings to ensure users get the most out of the device. After all, the entire world is facing a pandemic. This is not a competition. This is for the protection of the people using medicine, safety protocols, and engineering. Throughout this project we attempted to uphold the canons of the NSPE and ASME, by holding the safety, health, and welfare of the public paramount and by conducting ourselves honorably in interactions with our stakeholders and potential users.

APPENDIX Q: ENERGY BALANCE CALCULATION FOR TEMPERATURE/ HEAT ANALYSIS



APPENDIX R: LINK TO DEMONSTRATION ON LOW-FIDELITY PROTOTYPE

https://youtu.be/UtkW25tpey8