Designing a Waterless Disinfecting Household Toilet for Nairobi Slums

SOS Collaborative Final Report

CE 209: Design for Sustainable Communities

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Abstract

The spread of pathogens through human feces is a problem that the majority of the world population faces daily. Our project aims to minimize the possibility of this occurrence by disinfecting at the toilet. More specifically, this project's focus is to design a toilet, which incorporates the two-step Safe Sludge disinfection method and Sanergy business model. After an extensive design process, we have developed a proof-of-concept prototype comprised of three compartments and two transition valves. It has potential to be a disruptive technology if our recommendations for future work are considered. These recommendations include business model development, mechanical design improvement, and fieldwork to inform further prototype development.

Table of Contents

List of Figures and Tables

I. Introduction

Problem Statement

According to recent estimates, 4.1 billion people in the developing world lack access to improved sanitation, defined as infrastructure that prevents contact between humans and their waste[1]. Of this 60% of the world's population, 1.1 billion people practice open defecation and have no access to any kind of sanitation facility[2]. For those who do have access to a sanitation facility, their waste is excreted, collected, and transported to treatment facilities. In all the steps between excretion and treatment, there is a high potential for transmission of fecal-oral pathogens to spread to people who have direct contact with waste and other people with whom they interact. In many cases, fecal sludge is simply dumped out of sight from urban or affluent areas; even if it is treated, it is often not done enough to prevent pathogen transmission. Our project aims to treat potentially pathogenic waste at the point of collection in order to prevent pathogen transmission downstream of the toilet. This intervention allows for flexibility in collection, transport, and treatment options while still ensuring the safety of people who come into contact with waste at any point in the sanitation value chain (Figure 1).

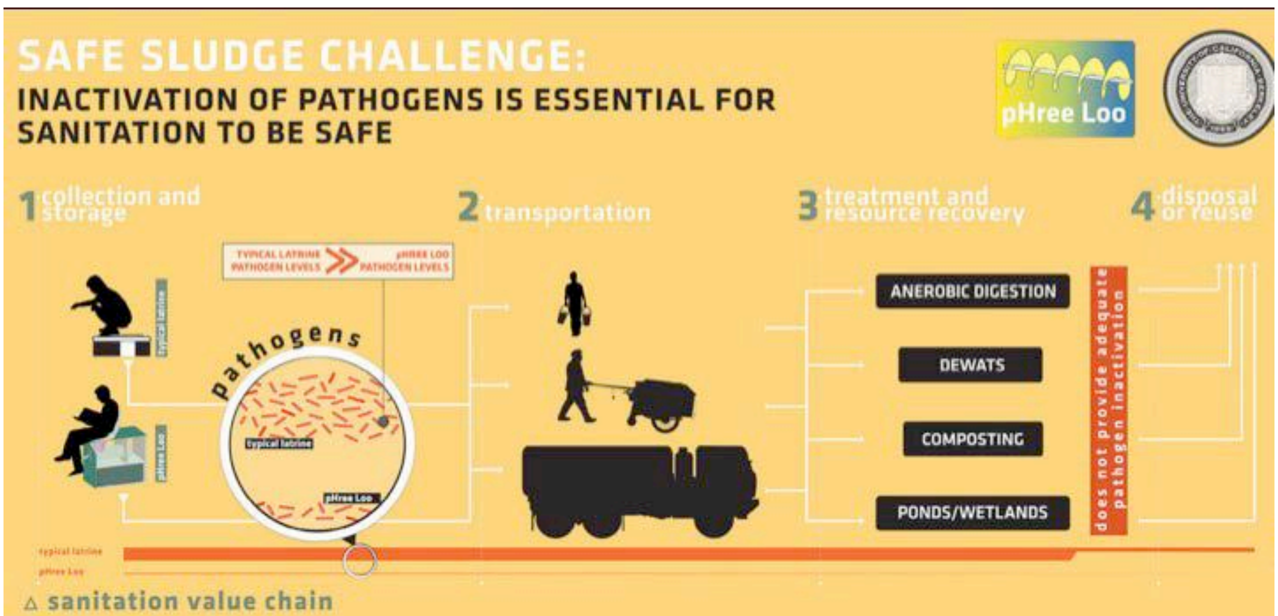

Figure 1. Sanitation Value Chain describing the potential steps waste takes from toilet to treatment. This chain does not apply for the 1.1 billion people who practice open defecation, as their waste is not collected.

[1] Sanitation: A Global Estimate of Sewerage Connections without Treatment and the Resulting Impact on MDG Progress Rachel Baum, Jeanne Luh, and Jamie Bartram. *Environmental Science & Technology* 2013 *47* (4), 1994-2000

[2] WHO and UNICEF (2012). Progress on Sanitation and Drinking Water: 2012 Update. Joint Monitoring Program. Geneva, World Health Organization.

Sanergy, a for-profit organization based in Nairobi, Kenya, currently builds and maintains community sanitation facilities to collect waste. After collection, it is put into digesters where it is sanitized and harvested for energy. Their toilets are pay-per-use franchises and have received international support and local patronage. At UC Berkeley, Professor Kara Nelson and Dr.Temitope Ogunyoku have developed a Safe Sludge process that disinfects sludge at the collection point. This process consists of two steps: (1) urease in feces and urea in urine react to create ammonium, and (2) lime is added to create more ammonia than ammonium in an acid- base equilibrium (Figure 2). Ammonia is a powerful disinfectant shown to reduce levels of bacteria, protozoa, viruses, and helminths according to WHO standards[3] (see Team Binder 1b. for background literature).

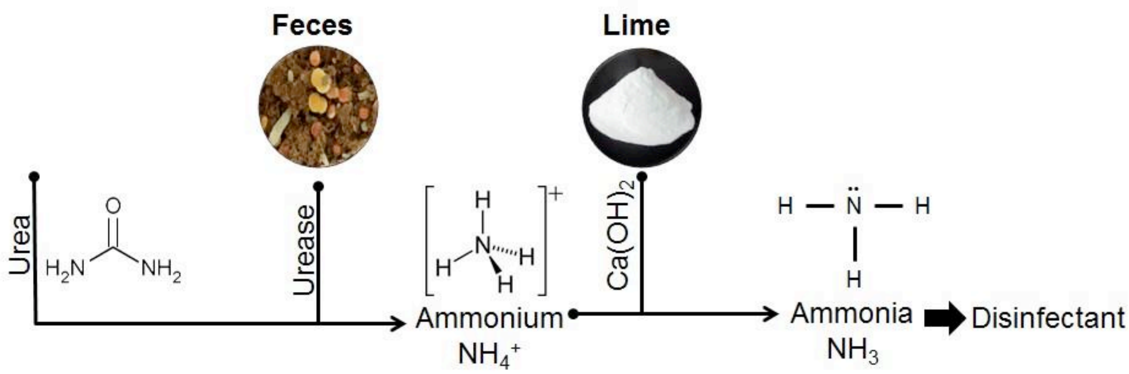

Figure 2. Chemical reaction for Safe Sludge process (Dr. Temi Ogunyoku). The two steps take place at different pH values and thus must be separated either temporally or spatially.

Approach

Our team's approach to eliminate pathogens combines the innovations and comparative advantages of our two partners (UC Berkeley's Safe Sludge and Sanergy) to design a waterless self-disinfecting toilet that incorporates the Safe Sludge process for a household that can be tested in Mukuru, an urban Nairobi slum. The Safe Sludge team has developed its process over the past year by testing inactivation rates of bacteria, viruses, and helminth eggs. Disinfection times have been shown to range from hours to weeks based on the type of pathogens examined and the desired inactivation. Tests have been conducted using laboratory setup and small sample sizes to allow for repeatability and laboratory detection methods. Our other partner, Sanergy, contributes a sound business model that has proven

[3] "WHO | Guidelines for the safe use of wastewater, excreta and greywater. Volume 1: Policy and regulatory aspects," *WHO*. [Online]. Available: http://www.who.int/water_sanitation_health/wastewater/gsuweg1/en/index.html. [Accessed: 04-Apr-2013].

effective for community toilets. In this system, entrepreneurs buy and operate blocks of community toilets as franchises and charge customers a fee per use. The waste is collected, composted, and sold for a profit to maintain the toilets and pay employees, known as the Clean Team[4]. So far, Sanergy has not expanded to household markets, focusing instead on scaling up their community model. Together our partners have established a foundation for our project that guides our approach as we extend their work to produce a household toilet prototype.

Another key part of our project approach was the dynamic mix of individual expertise on our team: Will is familiar with the Safe Sludge process, Kellie has water and sanitation fieldwork experience in Sub-Saharan Africa, Pierce has extensive CAD and design experience, and Angela has a systems implementation background. This diversity of experience came to bear at different points in our process. Familiarity with the Safe Sludge process allowed us to quickly conceptualize the theory behind it and apply our knowledge to incorporating the process into a toilet. Our collective experience in developing countries guided our decisions on what was feasible or infeasible for the user to do. CAD experience proved invaluable at the end of our process as we sought to sketch our proposed design and change dimensions before building, and previous building experience helped us think about how to design interfaces between chambers and also between the toilet and users.

In order to make progress on this multifaceted problem, we started with framing the problem and breaking it into manageable parts. There are many potential ways to improve sanitation in Mukuru ranging from developing a toilet prototype to minimizing the time required for disinfection, determining collection frequency, determining a cost structure, and scaling the entire solution up to other communities. We chose to focus on developing a proof-of-concept prototype that demonstrates that the Safe Sludge process has the potential to function in a household toilet. The scope of the project was further constrained by the desires of our partners: including the use of this process rather than other disinfection methods and using the household toilet context. Constraining our problem to this manageable deliverable proved to be a valuable first step in our process.

Our approach was adapted as we responded to challenges and discoveries throughout the semester. As we continued to define the problem, we identified key processes and technical challenges that served as handles we could grasp. We used these handles to design incrementally and prioritized them, which also proved a challenge. One of our major challenges was designing from afar, since we did not

[4] Sanergy website, www.saner.gy

have direct conversations with our potential users. Pierce has traveled to Kibera, another urban slum of Nairobi, and brings some valuable insight to our team; however, none of us have been to Mukuru and contact with Sanergy was limited. We also needed to make some progress first in order to ask informed questions. We mitigated this challenge of distance by getting user feedback from our classmates during our midterm design review. A final obstacle frequently encountered was the need to make decisions with limited information, especially as we sought to eliminate ideas and designs without actually building them. We concluded that our solution is one among many potential solutions and documented other ideas we discussed in the team binder (see Team Binder 3d).

Goals

For our original approach, we separated the design goals for our solution into four prioritized categories. We sought to design a toilet that: (1) effectively integrates the Safe Sludge process, (2) is market-competitive, (3) will continue to be used, and (4) can be duplicated and scaled to other communities. These goals were heavily influenced by our design constraints. Our team focused solely on designing a product (not a business model or a process), so our constraints were demanding but straightforward.

In order to design a toilet that effectively integrates the Safe Sludge process, the toilet must function properly and be robust enough to withstand use in harsher conditions than the lab settings in which we worked. Selling a low-quality toilet could damage relationships between our partners and the users, could be a waste of the users' limited money, and will not create progress toward improvements in sanitation. Creating a toilet that does not actually disinfect waste as it claims could increase rather than decrease the spread of pathogens.

The price of the toilet must be low enough to be a reasonable purchase in the context of Mukuru. The proposed system in our partnership with Sanergy would require households to pay for the toilet themselves. Even if we were to operate in the community toilet context instead, there is still the requirement for an individual household to purchase the toilet. With no estimation of the market size for our toilet, our team cannot rely on economies of scale to decrease our costs. While investigating the local supply chain was outside the scope of this project, our team aimed to use simple materials and mechanisms to reduce labor costs and simplify the supply chain. While our team was not able to get numbers for what would be a reasonable price for the toilet in Mukuru, our estimated value of $182.50 (10 users for 1 year at $.05/user/day) will require the toilet to have a simple design with inexpensive parts that are readily available, preferably locally. Our estimated value is likely to be higher than the price users are actually willing to pay since this price doesn't include the cost of the collection service. Our major competition is the status quo, either open defecation or flying toilets, both of which are extremely low cost.

Social acceptability is a larger concern in sanitation than most other spheres, and a harder one to get information on. Not only must the cost of the toilet be acceptable to the user, but also the toilet must be something that the user wants to and will continue to use. The current partnership between the Safe Sludge team and Sanergy does not provide for social marketing or NGO work to increase awareness of sanitation issues, so the product must be something that people want to use rather than a product that they can be convinced to use. In the context of Mukuru, we have assumed a household to be ten people living in a 10 ft x 10 ft room. The size of the toilet is therefore a large constraint since there is already a lot of competition for those 100 ft^2. Our estimated goal was to have the footprint be 6 ft^2 but we need more information to confirm that number. Odor and cleanliness of the toilet become a larger concern than they would be in a larger community toilet facility since people live in the space. Our chosen goal here was to have no noticeable increase in smell outside the toilet and have no visible feces. Finally, the actual process of using the toilet must be acceptable to the user. This includes ergonomics of the sitting and mixing as well as concerns such as sitting versus squatting that can damage sanitation projects. The process must also be acceptable to Sanergy and its Clean Team collectors since they are part of the collection process.

Scalability is the lowest of our priorities, but still is a necessary design constraint to consider. The simpler the design of the toilet, the more standardized the materials, the easier it is to be produced elsewhere. The chemical process and current toilet design requires a human-centered infrastructure of people to transport the treated sludge for external storage or use. This design works best in densely populated urban slum, like Mukuru, and is less likely to function in decentralized systems like rural areas.

Without close contact with Sanergy or people in Mukuru, many of these constraints remained solely qualitative design considerations, instead of tractable goals numbers that our project had to meet. Without numerical standards to check our progress against, we used these concepts as the basis of any design decision we made and they were a large part of our discussion. Certain design tradeoffs between user ergonomics, toilet simplicity, size, and cost were concerns likely at odds with each other, but could be considered with intuitive and educated analysis of toilet components. We turned these four constraint categories – toilet functionality, market competitiveness, sustainability, and scalability - into our project goals, and used the individual constraints as our metrics for project success (Figure 3).

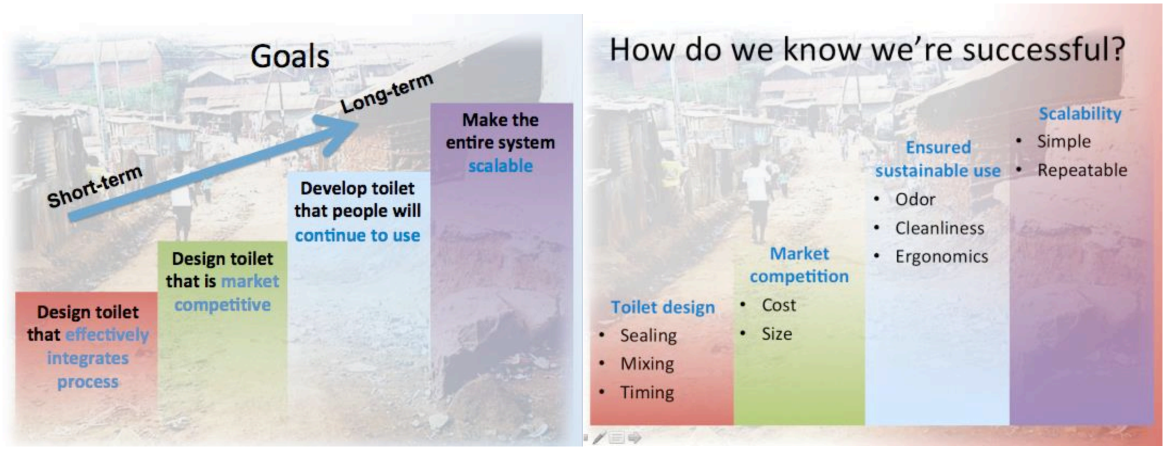

Figure 3: Qualitative metrics for Project Success. These design considerations framed the highest and progressively lower priority aspects of a successful toilet. It is likely, however, that all requirements must be fulfilled before a toilet can be considered for actual use.

Although we focused the vast majority of our time and effort on the first goal of integrating the Safe Sludge process into a toilet, we thought it important to identify long-term goals that informed our preliminary work. Our deliverables reflect our time allocation, and focus mainly on our toilet prototype. We have designed a proof-of-concept prototype that effectively integrates the Safe Sludge process (Team Binder 4b); a detailed CAD drawing of this prototype (Team Binder 5c); design trees of our prototype development (Team Binder 3d); an electronic team binder documenting our meeting notes, pictures, and idea webs; and this comprehensive report.

Proposed Solution

The current design solution uses a three-stage disinfection process. The sludge goes from the toilet bowl to a bag (chamber 1), where the user exerts a plunger motion on the object until it is thoroughly mixed. The user then activates the first valve, so the sludge can be contained in the 20-liter jerry can (chamber 2) for daily storage. Each day, the jerry can is emptied through the lower valve into the container that holds lime solution (chamber 3) for ammonia production, the last step of the disinfection process. A CAD of the current toilet design is shown below (Figure 4). In the sections that follow, we will discuss the process that resulted in this prototype, an evaluation of its merits and drawbacks, and plans for its improvement in later project phases.

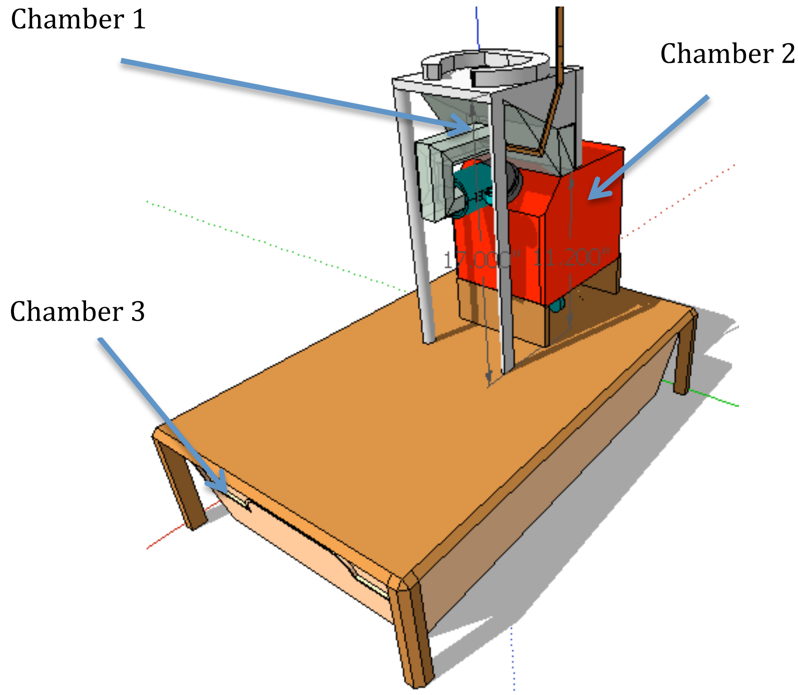

Figure 4. CAD design of current toilet design.

II. Project Narrative

Our project can be divided into six phases: definition, brainstorming, initial designs, refined designs, choosing one design, and construction. With our final prototype in mind, we can better examine the process by which we arrived at it.

Definition

As described in our approach section, we initially had to define our role in the project by balancing the goals of our two partners. We ultimately defined our goal as designing the physical toilet that would meet the characteristics listed above in our approach. This decision led to the requirements that the toilet to be a household toilet designed for a single family, and that the waste be completely sanitized before it is removed from the toilet. Discussions with Dr. Nelson and Dr. Ogunyoku also led to the assumption that the toilet would be operated in conjunction with a collection service such as Sanergy, and would require the same conditions for disinfection as used in the lab tests (four hours at low pH before lime addition and complete mixing of feces and urine). With these constraints in place, we isolated four different elements that we must adequately address: mixing of urine and feces, timed transport of the excreta, sealing, and cleaning, all of which we explained above. We initially developed a metaphor of a cow to represent each of these components: each is necessary, but they cannot function without the other. We planned to address each of these four stomachs and then connect them together to build a complete system.

Brainstorming

Brainstorming occurred in two phases: individual and collective. Each team member was assigned one of the four challenge elements to research in depth. We then came together as a team, shared our research, and added in ideas from other team members. We then solicited feedback and ideas from our mentors Jonathan Slack, Howdy Goudey, Marc Muller, Kirk McCarthy, and Tim Anderson. The results of this brainstorming were five idea webs, one for each of the four challenge elements (mixing, transport, sealing, and cleaning) and one for lime addition. At this point, the team assumed that mixing would be the most challenging, and critical working element, so we scavenged the hardware store for ways to test the capability of our proposed mixing mechanisms. These low-fidelity prototypes of the mixing component showed that some of the proposed mechanisms were not effective, but varying geometries of the eggbeater, salad spinner, and food mill could potentially meet the requirements for mixing (see Team Binder 3e, 3f).

While we tested these materials we came across critical mixing design considerations. For replacement and cleaning purposes, it is better to have an object that mixes without touching the excreta, such as a rolling pin or a masher that mixes the waste in a plastic bag. Some mixing mechanisms, like a food mill or a blender, cannot operate without touching the material. Other considerations include how to mix an entire chamber of waste and how to deal with the continuous addition of waste to an already mixed system. In our discussions and experiments, we explored ways to batch a continuous flow by quantizing waste for each use and collecting for a day before mixing. Results from our mixing experiments can be found in Table 1.

	Miso Alone	Miso and Water
Food Mill	-residual on blade/stirrer -hard to turn at first	-most water goes straight through and just makes miso more sticky so we get more residual
Potato Masher	-gets stuck from suction if you push down too much -need to change directions /have	-more suction than with only miso -makes a cake-like/waffle-like structure with squares that do not go into sludge form
Egg Slicer	-sticks to blades -hard to clean	N/A
Egg Beater (horizontal)	-pieces can pass through between the blades unless the egg beater is turned quick enough	-splatter -still chunky -sticks to egg beater components -hard to clean
Egg Beater (vertical)	-need lateral movement +decent mixing job	

Table 1. Mixing results. (+) is a pro, (-) is a con.

As we tested mixing alternatives, we also thought about whether they would be better suited to mixing urine and feces before or after lime addition. In order to make this decision, we performed a number of back-of-the-envelope calculations to estimate how much mixing would be needed. Mixing occurs twice in the process: once with feces and urine to make waste slurry, and once after lime addition to distribute the pH increase that converts ammonium to ammonia. Although we hypothesized that the former process would take more energy, we confirmed our intuition from the following chemical reactions and associated energies:

$NH_2CONH_2 + H_2O \rightarrow 2NH_3 + CO_2$ $\Delta H = 35.5$ kJ/mol

$Ca(OH)_2 \rightarrow Ca^{+2} + 2OH^-$ $\Delta H = -16.71$ kJ/mol

$NH_4^+ + OH^- \rightarrow NH_3 + H_2O_{(l)}$ $\Delta H = 31.1$ kJ/mol

where the first reaction shows the hydrolysis of urea to ammonia, which occurs when urine and feces are mixed and has a reaction enthalpy of 35.5 kJ/mol. The mixing in of lime combines the second and third equations for a total reaction enthalpy of 45.5 kJ/mol. Although it may seem like the second mixing step takes more energy than the first, this is only a consideration of chemical energy; we also aim in the first step to break up solid pieces of feces into smaller and more malleable pieces to form a urine-feces slurry, which will take substantially more energy. We used these calculations and considerations to prioritize mixing of waste over mixing of waste and lime in our design process (see team Binder 2a (endothermic calculations), 3a (Experiment SOP)).

Initial Designs

When we started to combine our challenge elements into designs for the whole system, the team met its first real unexpected problem: how to power our toilet. We had limited power inputs, effectively relying on human power supplied by the user in order to keep costs and design feasibility within the required range. Power then became an additional challenge element (in addition to mixing, transport, sealing, cleaning, and lime addition) that must be incorporated into our designs, but this time we were unable to use low-fidelity prototypes to narrow our selection. At the same time, pairing all the power methods with all the mixing mechanisms was unreasonable given our project budget and duration, and testing the power method by itself would provide only limited insight into how it would work within a system.

The team finally settled on an approach where each person drew out a complete system prototype with the understanding that the power mechanism could be exchanged for another if the low-fidelity prototype proved inadequate. We listed our options for each of our current challenge elements (mixing, timing, power, lime addition, sealing; Figure 5). We used predictions, discussion, and our experiments to narrow down the number of designs. For example, if you use a food mill to mix the excreta, it works best with a rigid holding cell that the mill can be held in, not a flexible plastic bag. If you use a salad spinner to mix the excreta as a whole, it is harder to design a low-power way to create a feed tube with a one-way valve that opens with minimal outside intervention. Choosing individually also allowed team members to pick their favorite option for each element or what they thought most promising. A detailed drawing of each member's design was compiled into a single file and taken to our mentors Jonathan and Howdy for review before we began low-fidelity prototypes of the entire system (see Team Binder 3c). That was where we ran into our second problem.

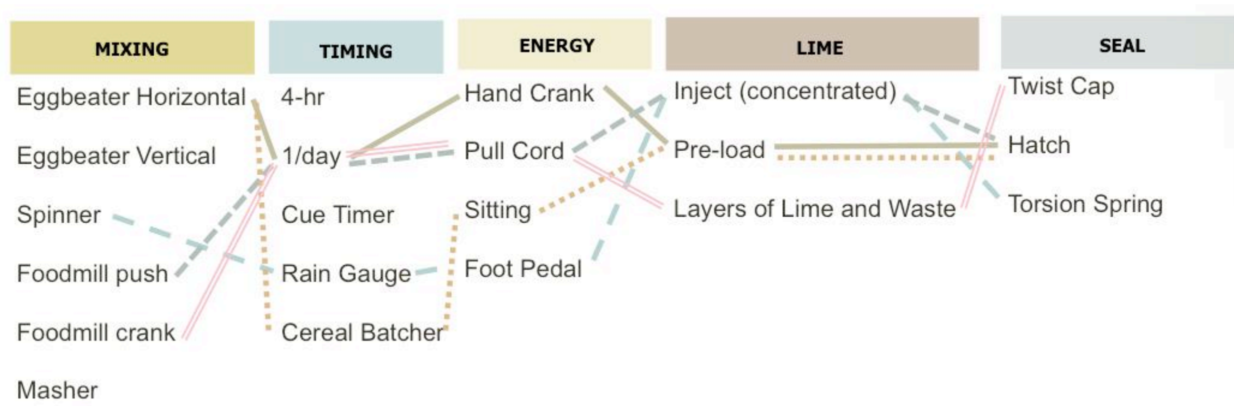

Figure 5. Matrix of five of six challenge components. Here mixing, timing, energy (power), lime addition, and sealing are shown. We chose to save cleaning for after our designs were more concrete. Lines connecting elements in different columns show the different prototypes designed (Team Binder 3d).

A common theme through all of the feedback we received from our mentors was that our designs needed to be simpler. In an effort to minimize the energy input, our mixing mechanisms used many moving parts and many parts that were in contact with the excreta. This would make maintenance and cleaning difficult, and inadequacies in these areas could harm the disinfection process. We initially took this feedback as a setback, an indication that we had been moving the wrong way with the project. However, further discussion led to the conclusion that we had made some progress but needed a second round of designs before we invested money in building prototypes.

Refined Designs

We modified our initial designs by incorporating the feedback of our mentors. We still tried to keep a variety between our designs so that we had a wider range of designs to get feedback on from the class. Ultimately, we created four low-fidelity prototypes.

(1) Plunger and bag design- In this simple design, the user excretes into a bag. Then the user mixes his or her own excreta by activating the plunger. All actions are human-powered. This design focused on mixing. Moving the excreta from the bag to another compartment was only to be considered in future designs if the mixing mechanism was desirable.

Figure 6. Plunger and bag design.

(2) *Peristaltic pump design*- In this design, the user excretes into a funnel like toilet bowl which moves the urine and feces into a tube. Once in the tube, the feces is mixed and transported by a peristaltic pump. This peristaltic pump would be powered by a human turning a crank. The excreta would stay in the tube until it had the proper ammonium content. Then, it would come out of the tube into a separate lime compartment. Multiple lime compartments were provided to see if users preferred smaller more manageable containers or larger containers that they would have to deal with less often.

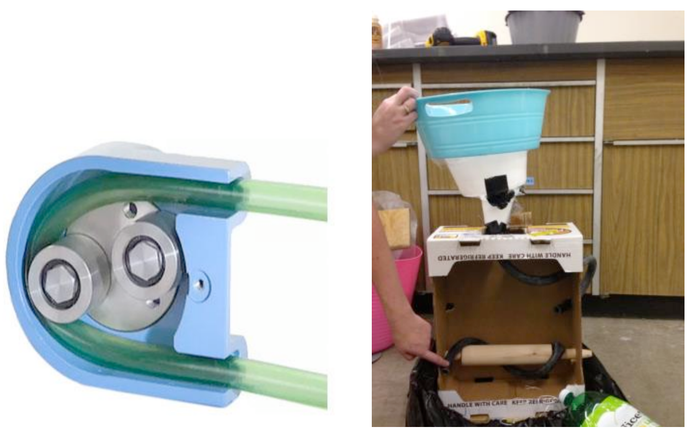

Figure 7. Peristaltic pump and Peristaltic pump design.

(3) *Food mill design*- In this design, after the user excretes into the toilet bowl, he or she powers a food mill with a foot pedal to mix the urine and feces. Then, the mixed excreta go into another compartment where it sits for a day before being emptied to the final lime compartment. A 2L bottle was used to represent the use of multiple small containers that must be exchanged often.

Figure 8. Food mill design.

(4) *Eggbeater design*- In this design, the user's excreta in the toilet bowl is funneled down into a small mixing compartment where it is mixed with an eggbeater. Then, it will empty into a compartment where it sits once a day. This design has two once-a-day compartments so that the toilet can still be used while the excreta is slowly moving from the once-a-day compartment to the final lime compartment.

Figure 9. Eggbeater design.

Design Choice

We presented the four low-fidelity prototypes to our classmates, professors, and mentors during our midterm presentation (see Team Binder 5b for notes and feedback). After presenting our four refined designs, we decided that people would rather deal with larger lime containers than the daily use ones even if they are less manageable, but these containers had to be small and light enough to be easily carried by an average adult when full. We also learned that the designs in which the feces and urine are not directly in contact with the mixing mechanism are highly preferred. Thus, we had narrowed our designs from four to two: the peristaltic pump design and the plunger and bag design.

After deciding on two designs, we sought the advice of our mentors again because we were having difficulty creating the peristaltic pump. Furthermore, we could not figure out an easy way to get the feces into the small opening of the tube. We also considered larger tubes, but they were much too expensive. Thus, in the end, we chose the plunger and bag design to be made into a full-scale medium-fidelity prototype. (see Team Binder 4b for further explanation, CAD model pictures, and important dimensions).

Now that we had chosen a mechanism for mixing, we had to determine many more details, such as sealing and transport. Jonathan and Howdy suggested we use ball valves for sealing and gravity for transport. Thus, our final design had three compartments: the mixing compartment, the once-a-day storage compartment, and the lime container. After every use, users must activate the plunger mechanism and turn the ball valve between the mixing and once-a-day storage compartments. This valve will allow the most recently mixed excreta to join the previously mixed excreta in the temporary storage unit. Once a day, the ball valve will be turned to allow the sludge (feces and urine mix) to be mixed with lime in the lime compartment. The specifics of the design, such as the sizes of the bags, how much mixing is needed, and how much water must be in the lime solution were still unknown, so further tests were conducted.

Design Experimentation

The bulk of our laboratory experiments were conducted to answer questions about the moisture content of feces simulant and the minimum amount of water that would need to be added to solid lime in order for mixing to occur between lime paste and waste slurry. Moisture content tests were conducted according to moisture content standard operating procedures (see team Binder 3a)[5]. Three samples of about 100 grams of miso were weighed, dried in an oven at 110 °C, and weighed again. The loss of mass was attributed to water loss, and divided by the original mass to determine moisture content. The motivation of this test was to determine the moisture content of miso and alter it later to adjust to the 75% moisture content of feces to make our mixing tests higher fidelity. The average moisture content of miso was calculated to be about 56%, meaning that water should be added to miso

[5] Adapted from Questa Rock Pile Stability Study SOP 40v10.
http://geoinfo.nmt.edu/staff/mclemore/projects/environment/documents/SOP_40v10_Moisture-Content_final.pdf

to make it a better feces simulant. Without this correction, we would be overestimating the mixing needed. Moisture content can be easily affected by miso storage, so we were careful in all our laboratory tests to use freshly opened miso. Doing this for prototype mixing tests is also advised to avoid confounding miso preparation and storage with actual mixing experimental setup.

Wet miso mass (g)	Dry miso mass (g)	Water (g)	Moisture Content (%)
99.55	43.84	55.71	55.96
97.08	43.01	54.07	55.70
100.46	43.29	57.17	56.91
		Average	**56.19001211**

Table 2. Moisture content records.

In order to determine the minimum water volume needed with lime powder in the final lime container, five 330 mL aliquots of waste slurry simulant (distilled water and miso) were prepared and tested with five lime pastes containing the same lime mass but different water volumes: 0, 10, 50, 100, and 250. The simulant slurries were made using a 2.57:1 urine-feces ratio as suggested by our mentor Dr. Ogunyoku. The water volumes were chosen to include no water at all (0 mL), the same amount of water as urine (250 mL) or fees (100 mL), and half (50 mL) and a tenth (10 mL) of the feces amount. pH was used as a measure of mixing by measuring it in the center of each container and at the edge in the four cardinal directions (north, south, east, and west). Measurements were taken at 0, 1, 2, 4, and 24 hours after mixing the waste slurry and lime paste. The standard deviation of pH measurements for each lime-waste mixture was interpreted as a proxy for mixing where high standard deviation indicated poor mixing and low standard deviation indicated a well-mixed sample at a given time point.

The sample with no water added showed drastically different results from the other four samples, so analysis was conducted with and without the no-water control. This sample showed much lower pH and a higher standard deviation (less mixing) than other samples (Figures 10,12). For the rest of the samples, pH increased with time for the first six hours for but seemed to reach a maximum level and drop slightly for the 24-hour time sample (Figure 11). Mixing fluctuated at early times but settled on a steady state value after about six hours; it also improved with volume of water added (Figure 12).

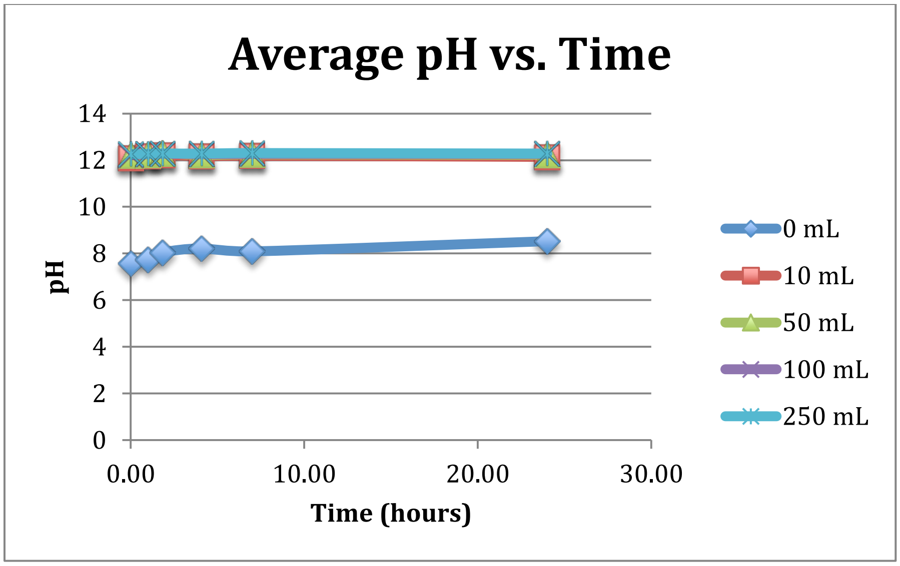

Figure 10. Average pH vs. time for all samples. The no-water sample showed a pH value far below (4 pH units) the other four samples.

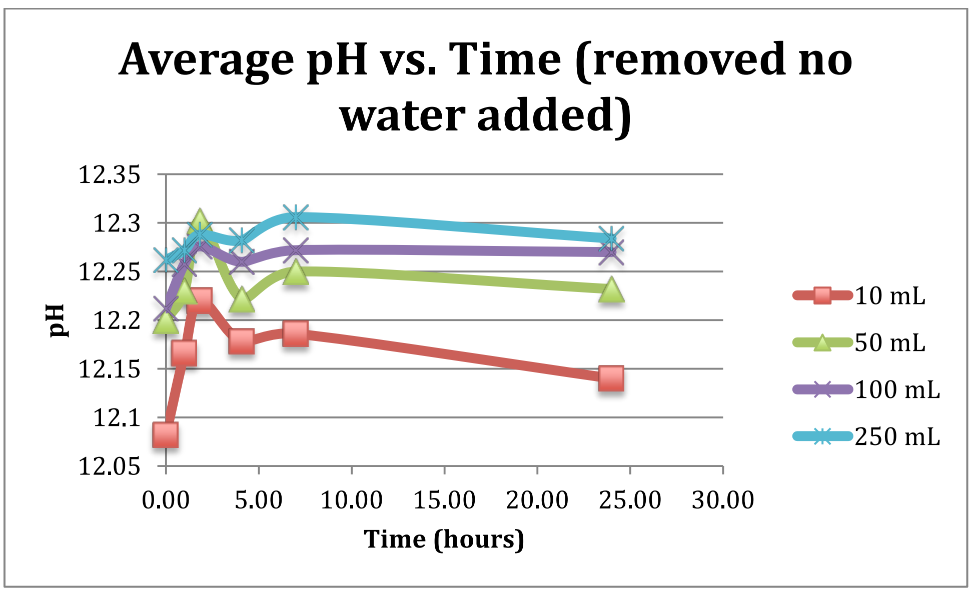

Figure 11. Average pH vs. time for watered samples. All pH measurements were above pH 12. All samples showed a slight decrease in pH from 6 hours to 24 hours.

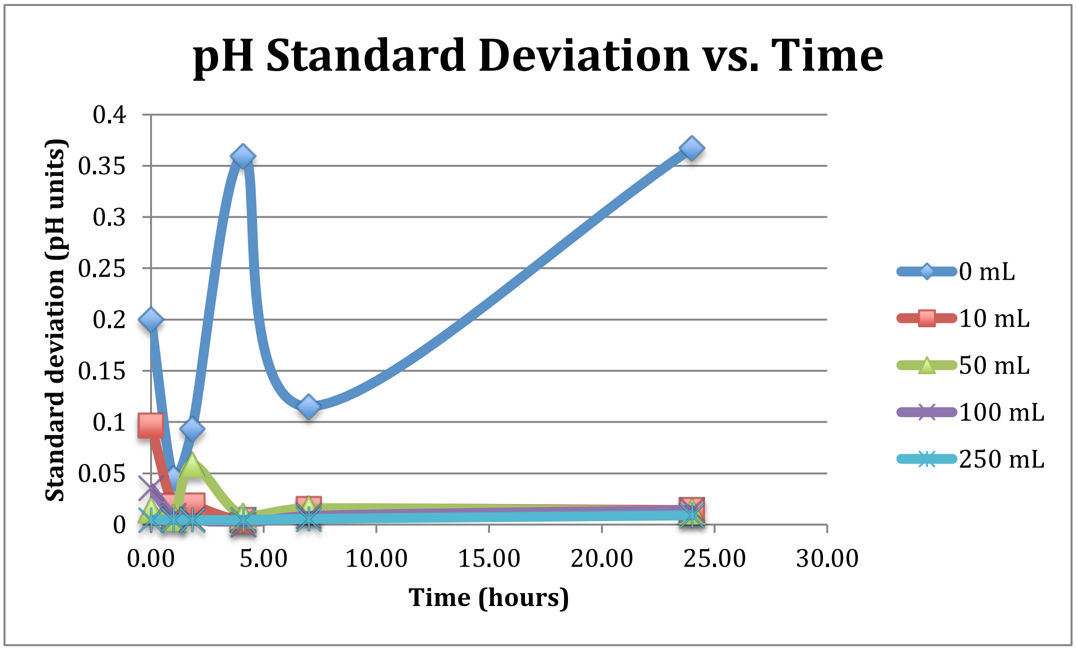

Figure 12. Standard deviation vs. time where standard deviation is a measure of mixing. Again the no-water sample is an outlier, but this time with a higher standard deviation than the other four samples.

The minimum amount of water needed in the lime paste was determined to be between 0 and 10 mL (based on comparison with the larger volumes) relative to 330 mL waste slurry. This means the water-waste ratio in the lime container should be at least 3%, representing the 10 mL water to 330 mL waste ratio. This proportion depends on the desired mixing of the lime container, which could depend on business infrastructure inputs that affect mixing like how long the container is stored before disposal, how it is transported, and how it is emptied.

Construction

A key factor in sizing our prototype was the amount of waste it had to hold at any one time. Based on an assumption that the Sanergy Clean Team would collect each household's waste on a weekly basis, we determined the necessary volume of each chamber of our toilet. The average person excretes about 1 L of urine and 0.5 L of feces each day, for a total of 1.5 L. We estimated a household to be ten people but average out to seven adults when combining children's waste to be that of the average adult. For an average of seven adults, that makes 10.5 L of waste each day, or 73.5 L of waste between collections. Given that this would weigh about 73.5 kg (assuming waste has an average density similar to water, 1 kg/L) we decided to split the lime container into two 40-L containers so that each household would be able to switch out its waste and Clean Team members would be able to carry the final waste container.

For the daily chamber, we used the 10.5 L waste/day for each household and applied a safety factor of about 2 in case users forget to empty it daily for a total volume of 19 L. For the bag that we will encourage users to empty after each use, we calculated a volume of 4 L based on the assumption that if it should hold two people's daily waste and have extra spacing for mixing.

The sizing of the three chambers governed the rest of our prototype construction. Once these volumes were determined, we created a vertical profile of the toilet and used the standard 17.5-inch distance from seat to feet to construct the superstructure of the toilet, including steps and platforms to conserve the seated toilet experience.

The materials for our toilet were determined by price and availability (see Team Binder 4a for cost information). The framing of our toilet is made with plywood and wood. The toilet seat and toilet bowl is pre-fabricated plastic. The internal workings of our toilet consist of a heat-sealed plastic bag, PVC pipes, ball valves, a jerry can, a union fitting, and a plastic container. After buying the materials we needed and measuring and cutting our materials to the proper shapes and sizes, we proceeded to construct the medium-fidelity toilet.

The plastic bag functions as our mixing compartment; the jerry can functions as our once-a-day storage compartment; and the plastic container functions as our lime container. The mixing compartment and once-a-day storage compartments are separated with a ball valve. This ball valve is to be turned after each use. The once-a-day storage compartment is then separated from the lime compartment by another ball valve and a union fitting. This union fitting allows the lime compartment to be exchanged with an empty lime compartment without fecal sludge dripping.

III. Evaluation

Sustainability

Planning for sustainability is important during the design process because if the final product and its services are not sustainable, the system will likely fall apart as soon as we stop intervening. Therefore, our team considered the following five points: (1) technical feasibility, (2) financial viability, (3) local affordability, (4) desirability, and (5) scalability.

Technical Feasibility

Our designs are technically feasible in the sense that the toilet effectively incorporates the Safe Sludge process. In other words, the different components of the toilet must work together to effectively mix the urine and feces together, and then this mix must remain together for at least four hours before lime is added to it. After the lime is added to the mix, the sludge can sit in a compartment for an adequate amount of time (at least one day for optimal pathogen reduction) before it is removed by Sanergy's collection team. When the Collection team comes to collect the sludge, it has already been sanitized. Because of the process, the Collection team, the household members, and any other potential disease-carrying individual are at low risk of coming into contact with unsanitized feces and urine. In other words, the design successfully reduces pathogen levels using the Safe Sludge process.

Financial Viability

The household toilets themselves will have to be purchased by the users. The users of the toilet will also pay for collection of the sanitized sludge. This will help pay for the Clean Team's wages. We do not know how much people are willing to pay for each collection, but we do know that Sanergy is charging for the community pay-per-use toilets and that they are making a profit. Thus, we hope that Sanergy can follow or adapt a similar pricing scheme for the household toilets. Unfortunately, we, as well as our partners, do not know how much people are willing to pay for household toilets, and as of now are still waiting on financial information from Sanergy. However, as there are multiple options for financing in the Nairobi area, we hope options for outside financing can be considered in future analyses.

Local Affordability

Although we had trouble finding particular cost constraints due to Sanergy communication issues, local affordability was a constant design consideration. Our design is both compartmentalized and modular: if a specific compartment breaks only that compartment needs to be replaced. For example, if the bag begins to leak, only the bag needs to be replaced, and the bags will be kept in a separate compartment that can be replaced as a whole. However, contamination is possible when replacing specific compartments, so the replacement must be completed with care. Moreover, there are many components in the toilet that may be especially difficult to replace once they are broken, such as the ball valves. If the valves are broken, the whole toilet may need to be replaced. The largest cost materials are likely to be the ball valves, and the union fittings, which meant the cost should be at least $200 USD. We know that we must focus on simplifying our toilet design so that it is locally affordable. The materials chosen to make up the toilet must also be local materials in order to minimize the cost of the toilets. In fact, the compartment between the two valves is actually a jerry can, so replacement of that compartment should be easy.

Desirability

Since 1.1 billion people, or 15% of the global population, practice open defecation and have no access to sanitation facilities, these people may have a strong desire to have a household toilet, especially if they are informed of the dangers of open defecation and benefits of sanitation. In order to make the toilet desirable, we must take advantage of Sanergy's good reputation of being very clean. Another way to motivate potential users is to educate the people regarding the health benefits of using the toilets. Though we are not in the position to market the future abilities of our prototype, we are actively considering our other design elements, such as odor, cleanliness, and ergonomic design. In other words, we will try to minimize the size of our toilet and minimize odors coming from it so that it can fit easily in a one-room home without disturbing the residents. Furthermore, a partition for privacy should be included with the toilet so that users are comfortable using the toilet when others are in the room.

Scalability

Simplifying the toilets and reducing their cost will eventually allow the toilets to be mass-manufactured so that they and the collection scheme can be expanded to nearby areas. Then Sanergy's collection team can collect more toilets in a given area, increasing their efficiency and profits, and allowing for more expansion of the business. However, the system requires that there is a dense enough population for the toilet collection service to be profitable. Moreover, there must be some established excreta collection company similar to Sanergy if the system is to be replicated because someone must come every week to collect the excreta and replace the lime containers.

Stakeholder Analysis

Another critical aspect of developing a successful design of our sanitizing toilet is the stakeholder analysis. The process identifies all individuals who directly impact or are impacted by the technology, business plan, process, or design used as well as providing a framework to analyze how these individuals interact, what they mean to our design, and how much interest they are likely to have in its progress. Each stakeholder is analyzed for its power over the project, its stake, or what it stands to lose or gain from the project. This framework identifies existing institutions and can be used to develop strategies for stakeholder participation based on stakeholder importance. These stakeholders can be analyzed in a two-dimensional framework, which shows the members' stake and their power over the project.

Once our team began this analysis we discovered two nuances that this framework could not display in its initial conception. "Stake" was not an adequate way of describing the risk-reward balance in this situation. Some stakeholders (e.g. local manufacturers) would have a large reward if the project were successful but would revert to the status quo with no negative repercussions if the project failed. Some stakeholders (e.g. current community toilet operators) would see declining business if the project was successful but would also return to the status quo if the project failed. Others such as Sanergy or users who buy into the system do not have the option of returning to the status quo. Our proposed model then used "stake" as a measure of the maximum difference in outcomes for that stakeholder between any of the possible scenarios for our project (success, failure, status quo, or varying degrees thereof).

This idea prompted a need for an understanding of how this two-dimensional framework changes in time, the second nuance. Some stakeholders were vital for design development and implementation but would no longer be involved once the process began operating while others might appear as the system is operational and the technology is disseminated to other communities. To depict this difference, we developed two tables, one showing the development and implementation phase of the project, and one showing the stakeholders once the project had been established and was running at full scale (Table 2).

Current Stakeholder Analysis	High Stake	Medium Stake	Low Stake
High Power	Sanergy	UCB Safe Sludge S.O.S.	Gates Foundation, Our Funders (Banks, NGOs)
Medium Power	Toilet users, Sick Mukuru Residents		Local Manufacturers, Local Government
Low Power		Mukuru Community Organizations	Project Mentors, National Government
Future Stakeholder Analysis	**High Stake**	**Medium Stake**	**Low Stake**
High Power	Sanergy	UCB Safe Sludge	Gates Foundation, Our Funders (Banks, NGOs)
Medium Power	Toilet users, Sick Mukuru Residents	**Local Manufacturers, Community Franchise Operators**	Local Government
Low Power		Mukuru Community Organizations	National Government, **S.O.S.**

Table 3: Present and Future stakeholder analysis. Present analysis refers to who currently impact the plan of the S.O.S. toilet business model, and future refers to who we expect the plan to impact, once the business is sustainable.

The key players that emerge in both cases are our two partners (UCB Safe Sludge and Sanergy) as well as the toilet users, especially those prone to illness. A trend also emerges where the stakeholders with high power over the project (S.O.S, Gates Foundation, etc.) are far away, comparatively wealthy, and have arguably a less long-term need for the project's success as a whole. However, the users and Mukuru residents, those most directly affected by the project, have less power and less responsibility for the project's success. Our team needs to address all three of these stakeholders then in order to move our project forward.

UCB Safe Sludge is still interested in this project as it represents the implementation of their work. Their support, especially their technical knowledge and lab expertise, is a substantial asset to the project and will become even more important as the prototypes enter the testing phase. Their continued support can be encouraged by offering this project in future offerings of this class, especially if combined with business students interested in relevant market studies.

Sanergy is interested in the project but is not as committed as we were originally led to believe. While they are interested in household toilets they have currently committed their money to expansion of their proven toilet system and wouldn't have the resources to integrate our toilet design with their collection system in the near future. However, they are a potential resource for local information. This relationship is maintained through our UCB Safe Sludge partners so our team doesn't have much power here. However, we can keep UCB Safe Sludge updated on our progress and encourage them to pass the information on to Sanergy.

Toilet users are stakeholders that could potentially help the project but have more control over its failure. If the users don't choose the new design over the status quo then the project will fail. If they are interested in the toilet, their input can help improve the design. Getting the users involved in the process is beyond the scope of our team's project. However, we anticipate that Sanergy will need some sort of marketing and demand generation. The implementation of the project will be expansion into a new market and the funding source for that venture is still unknown. Sanergy may have to involve community organizations and/or local government in order to increase demand. This cost may get passed on to the user in increased toilet prices, an adjustment ay future teams must consider. While we will not be the ones to develop these relationships, we can support the process by developing a good product and offering information and documentation to whoever does develop these relationships.

Failures and Lessons

Although we achieved our overall goal of producing a full-scale medium-fidelity prototype, our design process was a continual process of making our goals more realistic. We originally hoped to make a prototype that would be ready for field-testing, but designing something functional proved far more challenging than we expected. We also hoped to gather more information on making our toilet more cost-competitive, but finding dependable and context-specific information on cost proved difficult. In addition, we prioritized function over cost despite thinking that we would pursue the lowest cost relentlessly at the beginning of our project. Ultimately, we adapted our approach to making something functional first and focusing on optimization in later iterations. We also experienced periods where we did not seem to have made any progress for a long period of time, especially when we changed directions significantly. Alternating between the details of one parameter and the big picture of the entire prototype and its connection to the collection infrastructure also proved challenging. We constantly stalled ourselves in trying to address all of the many design criteria, rather than first focusing on a couple aspects and then reiterating and upgrading the prototype to meet other aspects. Many of our challenges were results of the preliminary nature of our project. Our hope is that in addition to our deliverables, we have laid some foundational groundwork for future iterations on our prototype and for subsequent generations of the product that may completely rethink our approach.

IV. Next Steps and Conclusions

Recommendations and Future Work

Much progress was accomplished on the road towards a sustainable household toilet that sanitizes feces in the absence of sanitation systems. However, there is still much to be done. Because much of the project was obtained in the absence of on-site information, we consider fieldwork an important component that the next generation of SOS should start.

Price point analysis and acquisition. One of the most important questions that were never answered during the development of the current model, is what a feasible technology price point we should strive for. Making the toilet to that point, in fact, could be the difference between selling to houses or whole communities. This is a question that requires dynamic and consistent analysis and revising over the course of the next project cycle.

Business model generation. Alongside the technology, a model for picking up the feces, for using it for different uses, and a further analysis of supply chain, stakeholders, and other important topics of financial aptitude must be considered. User feedback is especially important in designing the toilet, so their concerns, needs, what they are willing to do, and what they are willing to pay must be researched.

Tool and goods inquiry. There is minimal knowledge of the tools, the manufacturing capabilities, and the workforce available to make such toilets in Nairobi. Local is likely better, and analyses of barriers and opportunities must be considered. The types of materials used and how they are put together would greatly affect whether or not the production of the toilets can be industrialized, which would, in turn, affect its scalability.

Further model refinement, modeling, and testing. The current model is still only medium-fidelity, which means it hasn't been designed for real sludge or to hold a person's weight. Thus, real excreta should be tested in a full-scale full-fidelity toilet. This way, functionality and acceptability of odor of the toilet in the home can be analyzed. How much excreta is caught in the bag and containers can be assessed to change bag shapes and materials. If odor is found to be a problem, different sealing mechanisms or more seals can be used.

The toilet must also be designed to hold the full weight of the user, which may determine what materials compose the toilet. Moreover, drastic downsizing is likely needed to even vaguely consider the technology a household success, and downsizing is also necessary for traveling and testing purposes as well. Downsizing can be accomplished by using smaller valves and shorter pipes, so researching different valves and pipes is advised.

Conclusions

From the size of our prototype, we have concluded that it is not currently viable for household implementation. It either needs to be downsized or reimagined completely, perhaps for a community toilet setting, where the technology might have less stringent prices restrictions. The question of household vs. public toilets is a current polemic in the sanitation field that our project has shed some light on.

Household toilets have several advantages, including their aspirational nature and the dignity that a family having its own private toilet brings. Having a toilet in or next to a home also reduces the risk of violence in public toilets, which, in some communities, have become centers for gang activity and violence against women. Furthermore, it is not considered safe to venture outside at night in many informal settlements, which makes the community toilets defunct during the night hours. Another advantage of household toilets over community toilets is that the United Nations does not define public sanitation as improved. Thus, installing household toilets makes progress towards the water and sanitation Millennium Development Goal to halve the number of people without access to improved sanitation. Although this may be an arbitrary definition, it has important consequences: funders are more likely to support projects that contribute to UN-sanctioned goals, such as household toilets over public sanitation.

Household toilets also have some disadvantages, especially in our context. There may not be sufficient space for a toilet of any appreciable volume in houses as small as those in Mukuru, especially when odor and cleanliness are taken into account. In addition, there may not be sufficient infrastructure or space for the Clean Team to collect frequently enough to make the toilet small enough to fit inside a house. Collecting frequently may also be prohibitively expensive and might require prohibitively complex infrastructure, especially in the crowded streets of Mukuru where space is a premium resource. A cocktail of vacuum trucks, carted pumps, and manual labor could be necessary to collect waste from each household, but altogether difficult to enact. The question of whether household sanitation is viable in Mukuru remains open, and would be a fitting extension to this semester’s project.

With all of our progress, challenges, and remaining work in mind, we do believe that our sanitation solution has the potential for sustained impact. An aspirational household toilet that can treat sludge at the point of collection has the potential to completely change life in developing communities like Mukuru. By taking into account our recommendations for future work, we hope the next generation of SOS will experience exponential progress and growth. A two-pronged approach involving both lab work and fieldwork leverage the synergy of technical and business considerations to implement our proposed solution. Our long-term goal of scalability may be far off, but we believe we have made tangible progress toward it, and that it remains worth working towards.