Development of Affordable, Aspirational Sanitation Products for Sub-Saharan Africa

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Abstract

Poor sanitation and public defecation result in millions of deaths and diseases globally. Currently, countries in Sub-Saharan Africa have neither stable nor effective sanitation systems. In order to improve this situation, a practical, inspirational, and affordable sanitation device was designed and prototyped. The device was first created using 3D CAD software and then a physical model was developed using an FDM 3D printer. This mechanism has the ability to give communities in Sub-Saharan Africa access to sanitary toilets, limiting the spread of life-threatening diseases.

1. Introduction

1.1 Reinventing the Toilet

In 2011, the Bill and Melinda Gates Foundation partnered with American Standard in an effort to to "reinvent the toilet" and ameliorate sanitation problems in developing countries. The organization announced, "By improving how we deal with human waste, we can save lives, improve child health, and ensure greater dignity, privacy, and personal safety."[1] It recognized that the absence of effective latrines in homes around the world is the source of substantial global problems including death, disease, and poverty. The Bill and Melinda Gates Foundation is promoting global hygiene by encouraging innovative developments that will lead to sustainable sanitation systems in developing countries. The non-profit organization partnered with American Standard, a leading toilet manufacturer in North America, to develop and market a latrine concept that is affordable and aspirational.[2]

1.2 American Standard and the Flush for Good Campaign

In 2013, American Standard responded with the SaTo Pan and the Flush for Good campaign.[3] The SaTo Pan is a latrine that is set in cement and utilizes a trapdoor and a water seal; the design specifically caters to the country of Bangladesh.[4] Coupled with the Flush for Good campaign, which donates SaTo Pans to developing countries, the affordable price of American Standard's product allowed for hundreds of thousands of SaTo Pans to be deployed in Bangladesh by the beginning of 2014. The Bill and Melinda Gates Foundation and American Standard intend to expand their market in order to improve sanitation in Sub-Saharan Africa, where the cultural conditions and climate of the region demand a new latrine design.[1]

1.3 Purpose

This project seeks to mitigate the sanitation crisis in Sub-Saharan Africa by developing an affordable and desirable latrine concept. This research analyzes the functionality and practicality of the proposed designs and culminates in a 3D prototype of the optimal solution.

2. Background

Worldwide, sanitation deficiencies are responsible for millions of deaths and diseases, making sanitation a serious, yet barely discussed, issue. Currently, 215 million people in Sub-Saharan African countries practice open defecation. This practice spreads disease by contaminating water sources through runoff.[2] Even areas that use pit latrines suffer from widespread illnesses. The vast majority of pit latrines are open holes that allow flying insects to land on exposed feces, come into contact with bacteria, and contaminate food supplies.[5] The tainted food and water is responsible for the deaths of more than 850,000 children annually. With improved sanitation, 88% of those children's deaths can be prevented. [6]

In addition to saving millions of lives, improved sanitation can save the region from losing billions of dollars through missed workdays and health care costs.[4] Lack of sanitation also severely impacts education. A study done by the London School of Hygiene and Tropical Medicine estimated that in Sub-Saharan Africa, over 443 million school days are lost each year due to sanitation-related illnesses.[6] Because of the increase in public health and productivity that would result from better hygiene conditions, improved sanitation can pay for itself. In fact, it is estimated that every dollar invested in sanitation will yield five dollars in increased productivity.[6] The development of an affordable and desirable latrine makes both economical and ethical sense.

2.1 The Effectiveness of the SaTo Pan in Bangladesh

Because of its success, the SaTo Pan, designed for the people of Bangladesh, served as the benchmark for the Sub-Saharan latrine concept. However, the SaTo works specifically with the bodna, a traditional Bangladeshi water jug used to flush toilets.[8] The flush-by-bodna system disposes of waste and creates an airtight seal, while also requiring no change in user behavior. The force of the 500 milliliters of water from the bodna opens the trapdoor and cleans the toilet pan. The remaining water acts as a cohesive, creating an airtight seal once the trapdoor is closed.

The SaTo Pan was successful in Bangladesh. By 2013, it was implemented in 500,000 households and American Standard projects sales to increase to 1,000,000 by 2015. In addition to being a commercial success, the SaTo Pan has greatly improved the sanitation system in Bangladesh; not only does it prevent flies from interacting with human waste and spreading disease, but it also makes private defecation a more attractive option than open defecation.[2] This added appeal is responsible for the exponential increase in sales of the pan and awareness of sanitation.[2] A similar toilet has the potential to comparably impact poor sanitation systems in Sub-Saharan Africa.

Figure 1. American Standard's SaTo Pan that demonstrates the trapdoor and counterweight mechanism. [7]

2.2 Differences Between Bangladesh and Sub-Saharan Africa

The SaTo Pan has limited effectiveness in Sub-Saharan Africa, where the resources essential to the function of American Standard's product, water and concrete, are scarce. Bangladesh has an abundant water supply and frequently experiences floods and monsoon rains that supplement its surplus of water.[9] Its developed industry also offers copious and available supplies of concrete.[10] The SaTo Pan takes advantage of those resources by operating a flush-by-bodna system and setting itself in concrete. The orientation and strength of American Standard's design was affected by the resources and habits of the inhabitants.[3]

The Bangladeshi population customarily squats during defecation and water-washes afterward. Because squatting is so ingrained in Bangladeshi culture, the SaTo Pan would have been ineffective as a sitting toilet. Although the implementation of American Standard's SaTo Pan improved the health and sanitation of the Bangladeshi people, circumstances existing in Sub-Saharan Africa necessitate a different approach.

Countries located in Sub-Saharan Africa are highly water stressed, meaning the demand for water exceeds its supply resulting in the deterioration of the quality and quantity of water.[11] Concrete is also a scarcity there, and, although the region develops plastic, its industry is fairly small relative to that of Bangladesh. As a result, most African people resort to making latrine floors from mud or wood. Culturally, Sub-Saharan citizens generally accept a wiping culture and in certain countries view sitting toilets as symbols of wealth.[10] Because the countries in the Sub-Saharan regions have higher average incomes than that of Bangladesh, they have greater purchasing power.[12] Modern appliances including cellular phones and televisions are diffused throughout these African communities.[6] Therefore, even the populations with the means to purchase toilets do not have the desire to do so.[13] These differences were taken into account when designing a latrine that was inspired by the SaTo Pan, but specifically catered to Sub-Saharan Africa.

3. Methodology and Experimental Design of Latrine Development

3.1 Identifying Criteria and Constraints

The goal of this project was to develop an effective and desirable latrine. The project mentors defined such as a toilet that optimizes sanitation, enhances user experience, minimizes the use of water, ensures a market, and utilizes the region's readily available resources. The product must also be scalable, cost-effective, and reliable. The criteria positively limited idea development and defined the ideal final product.

In order to ensure the design concept is hygienic, living organisms cannot contact the feces within the pit beneath the toilet. The time the user and the carrying insects around the latrine are in contact with the pit must be minimized. The longer the exposure, the more likely disease is to spread. A trapdoor that is closed during use most effectively ensures sanitation. It inhibits flies from leaving and entering the pit and limits odor escape.

The elimination of odors will also improve user experience. The fecal matter within the pit exudes a poignant smell that only an airtight seal can effectively suppress. Therefore, the toilet design must include an intense seal. However, it cannot use water cohesion to create that seal, as water is limited in Sub-Saharan Africa.

The latrine can utilize a maximum of 200 milliliters of water per use. Sub-Saharan

African countries are highly water-stressed and undergo severe dry seasons.[8] A water-flush toilet like the SaTo Pan could not effectively be installed in Africa. Therefore, an ideal latrine has a waterless flush. However, the environment allows for occasional water cleansing. Although a waterless toilet is more expensive to produce than the SaTo Pan is, the Sub-Saharan African population is wealthier than that of Bangladesh, and has the purchasing power to address that expense.

Despite having the money to spend on sanitation, African people generally do not have the desire to purchase a product. Therefore, the design must be aspirational; it must incorporate a desirable aspect—a lid or a sitting stool—to ensure that there is a market willing to purchase it.

In order to address another difference between the countries of Sub-Saharan Africa and the country of Bangladesh, the toilet design must cater to wood and mud pit covers. The SaTo Pan was set in a concrete slab, however concrete is not readily available in Sub-Saharan Africa. The toilet design must be furnished in the wood and mud pit covers to which the African population is accustomed. This is possible through plastic flange attachments.

The absence of concrete in the region is reconciled by its plastic industry. A plastic product can be manufactured in Africa, which would stimulate the region's economy and cut costs logistically.

Using recycled polypropylene plastic also mitigates expenses. The SaTo is composed of 80% recycled polypropylene and 20% virgin polypropylene. Polypropylene is abundant, inexpensive, and has a refined surface. Recycled material is even less expensive and just as effective in a latrine product. In Bangladesh, the SaTo Pan is produced at a cost of $1.50 per pan. In Sub-Saharan Africa, the cost of a SaTo Pan would range from $3.00 to $4.00. A toilet that can be sold under $10.00 in the region would be reasonably affordable for its residents.[8]

Another aspect of logistics is mass production. The design must be able to be mass-produced in order to be a viable, sellable product. It takes thirty seconds to create one SaTo Pan from an existing mold.[8] Simple injection molds and few parts are characteristics of scalable products. In order to ensure scalability, the design must be simple enough that it can rival the SaTo's production speed.

Ultimately, the design must be long lasting and limit behavior change. If a population needs to be taught how to use a product, it will be disinclined to purchase it. Behavior change would create confusion and significant maintenance could result in the breakdown of the entire system. The proliferation of the product cannot rely on its users; it must rely on the strength of its design. The toilet must be simple in order to ensure that it will not break easily.

Sanitation, desirability, and efficiency of the design will ensure a reliable and cost-effective product. By prioritizing those criteria, the team was able to explore concepts logically and with a defined goal.

3.2 Method

Once the goal was developed by the defined criteria and constraints, design ideas were explored. After collaborative ideation and sketched designs, the concepts were evaluated in a decision matrix.

The decision matrix was based on the product's criteria, and the SaTo Pan was used as the benchmark. The effectiveness of each design was compared to that of the SaTo Pan in a Sub-Saharan African environment. With the base value of zero, a maximum of two points were added or subtracted, depending on how much better or worse the concepts were in each category compared to the benchmark. Following the evaluation of each individual category, comparison of the total points for each concept exhibited that the Cam and Right Angle designs were the most promising.

	SaTo Pan	Hook	Table	Screw	Cam	**Right Angle**
Sanitation improvement	0	0	0	-1	0	**1**
Aspirational	0	1	1	1	1	**1**
No behavior change	0	-1	-1	1	1	**-1**
Reliability of system	0	-2	-1	-2	0	**1**
Cost effective/ logistics	0	-1	-1	-1	-1	**-1**
Efficiency (water)	0	1	1	1	1	**2**
Uses readily available materials (not cement)	0	1	1	1	1	**1**
Enhanced user experience	0	1	1	1	1	**1**
Total Points	0	0	1	1	**4**	**4**

Figure 2. Decision Matrix. See Figure 6-9 in the Appendix for completed design concepts.

As a result, the Cam and Right Angle designs were the two concepts drafted in Autodesk Inventor Professional. After evaluating the complexity of the 3D CAD projects, it was evident that the Right Angle design had the most potential. It uses simpler mechanisms and fewer parts.

The Right Angle's mechanisms do not require water for flushing, although some water will be necessary for occasional cleansing. Opening the lid will cause the trapdoor to rotate. Because the trapdoor is in the shape of a right angle, the bottom of the toilet is sealed when the lid is both opened and closed (Figure 3). The user defecates on the bottom of the rotated trapdoor. When the toilet lid closes, the trapdoor rotates back and the waste falls into the pit below.

The Right Angle best optimizes the criteria: the tapered edge of the trapdoor creates an airtight seal when it is closed, the part of the trapdoor that actually contacts the waste remains in the pit for the majority of the time, and the design is applicable in either a sitting or squatting toilet. This way, the design can cater to specific countries within the region.

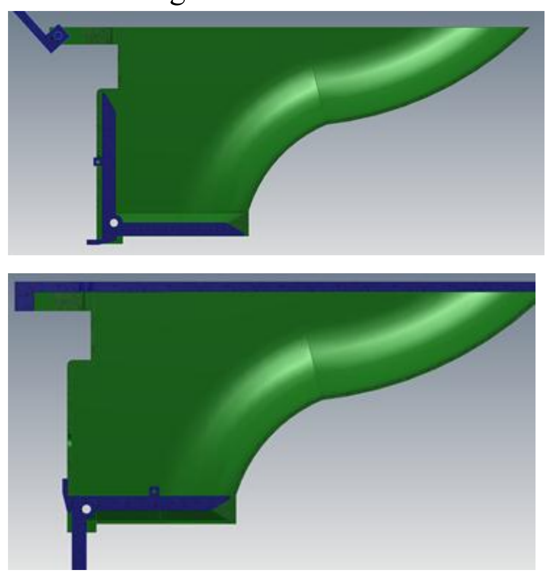

Figure 3. Right Angle design with open view, closed view

3.4 Experimental Design

The Right Angle design was the only toilet concept to be 3D printed by American Standard's 10"x10"x11" Fuse Deposition Modeling (FDM) machine. This machine printed the entire assembly using two resins, acrylonitrile butadiene styrene (ABS) plastic and a water soluble resin. The toilet components were printed using ABS plastic, and the supports using a water-soluble resin that dissolved away at the end of the process.[14]

The prototype was printed on a ⅔ scale of the CAD model, and the parts that were nonessential to the mechanics of the model were not included in the printing. It is important to note that the CAD model's dimensions were smaller than those of a full-scale model, so the prototype was more than ⅔ smaller than an actual toilet would be.

The prototype's lid was printed using the solid setting and the body was printed in high resolution. Some of the parts had to be sanded down afterward because the trapdoor did not smoothly rotate. However, this was due to a flaw in the printing and not the design of the model.

The scaled-down model used a polyester thread to connect the lid to the trapdoor, as it was thinner than a nylon fishing string, which will be used in the full-scale model. Nylon was chosen because, aside from being a material already available in Sub-Saharan Africa, it is extremely strong and resistant to wear and tear. This allows the design to be more reliable.

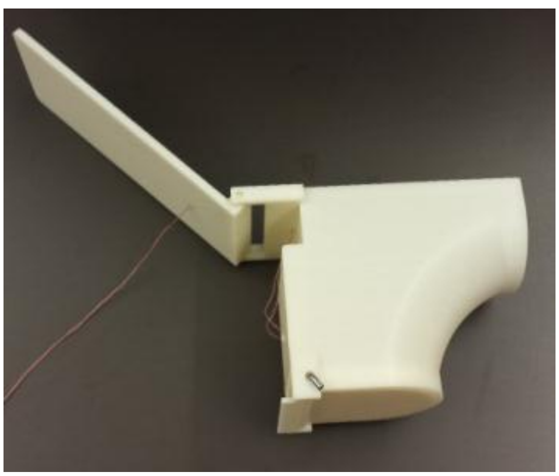

Figure 4. FDM printed prototype of Right Angle Concept

4. Results and Discussion

4.1 Testing Functionality of Design

In order to test the rope that connects the lid to the trapdoor, the lid was opened and closed. As the lid opened and closed, so did the trapdoor.

Filling the toilet with water tested the tapered seal. When the prototype was filled with water, most of the water drained out from the front of the trapdoor.

To test how well the toilet flushes, overripe avocado was used to simulate feces. Two tests utilizing two different consistencies of avocado were carried out to ensure that the toilet could function with different textures of fecal matter. First, avocados were spooned out; they held their own shape and were only moderately sticky. For the second test, avocado paste, which had a very soft and sticky texture, was used; it spread out when it was dropped.

Figure 5. Right Angle prototype before and after the avocado test revealing a clean flush and latrine interior. The prototype was lined with tin foil prior to conducting the tests to keep the prototype clean, preventing avocado from staying behind in the ridges of the toilet's rough surface.

4.2 Analysis of Toilet Quality

Three aspects of the toilet—the rope, seal, and flush—were tested for quality. The rope fulfilled its responsibility. It successfully functioned as a pulley that shifted the position of the trapdoor as the position of the lid changed.

However, the trapdoor was not closing completely during testing, which was surprising because the seal was supposed to be equally strong on all sides of the door. Upon investigation, it was discovered that the location of the rope's knot caused the failed seal. Although the trapdoor failed to seal the toilet completely, it still effectively flushed the simulated waste. Overall, the test results proved the design was functional and exposed the areas that needed improvement.

4.5 Limitations

Despite researching, designing, and drafting, the testing procedure still faced significant time constraints that made it impossible to evaluate the long term outcome of the design's function in Africa. Moreover, without effective materials and methods for prototype development, meaningful results could not be obtained. For instance, the prototype could not be used to test durability because the process that developed the prototype differs greatly from the processes used to make the marketable product.

Additionally, the amount of air that would be able to escape from the pit through the toilet could not be tested. The layer-by-layer additive manufacturing method that was used to fabricate the prototype cannot make the smooth walls that are required for an airtight seal. However, the polypropylene plastic of the marketable product has that potential.

The effects of thermal expansion on the plastic, rope-wear after years of use, and other characteristics could not be tested, either. The time constraints limited the testing process.

5. Conclusion

Based on an evaluation of the test results and advice from the project mentors, improvements on several aspects of the design were proposed, regarding either the function of the device or processes necessary to mass-produce it. Just before the trapdoor closes, the string pulls the door perpendicularly to the direction in which the lid rotates. As a result, trap door is not effectively pressed against the seal. Not only can the position of the rope be improved, but the amount of time that the rope spends in the pit can also be optimized. The current design is prone to contamination and bacteria transfer. Moreover, the lip on the back of the toilet requires the use of rotational injection molding, which complicates and lengthens production. The prototype was created using 3D printing techniques, but because the final product will be made using injection molding, the lip must be modified.

A rounded extrusion placed on the back of the toilet can supply the necessary force to ensure that the trapdoor is always being actively held up. The rope's function could be improved by encasing the section of the rope that is exposed to the pit in a hollow tube, thereby limiting the rope's exposure to the contents of the pit and guiding it in the correct direction. In order to decrease the cost and complexity of production, the back lip of the toilet can be replaced with a flat wall. Testing exposed these areas for improvement, and the results and experience defined possible resolutions.

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8. Appendix

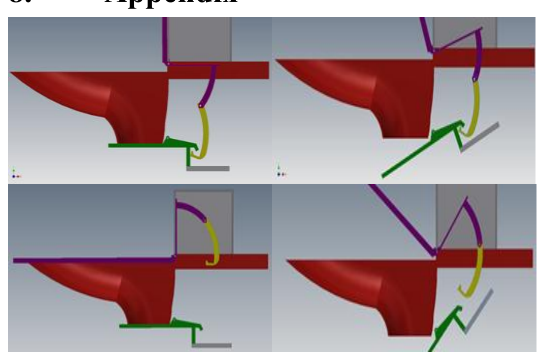

Figure 6
Hook draft in AutoCAD with exterior side view. These four pictures show the toilet closing in stages.

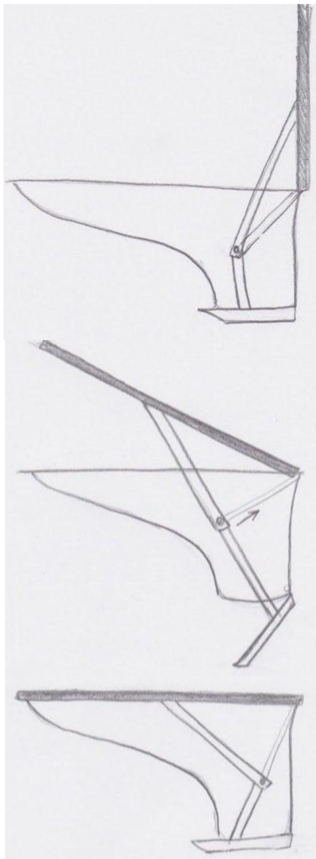

Figure 7
Table design sketched with open view, midpoint view, closed view

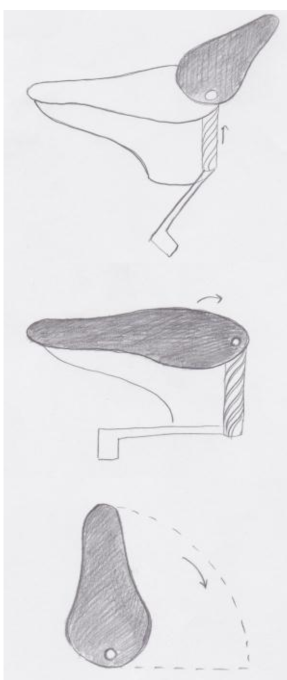

Figure 8
Screw design sketched with open view, closed view, top view

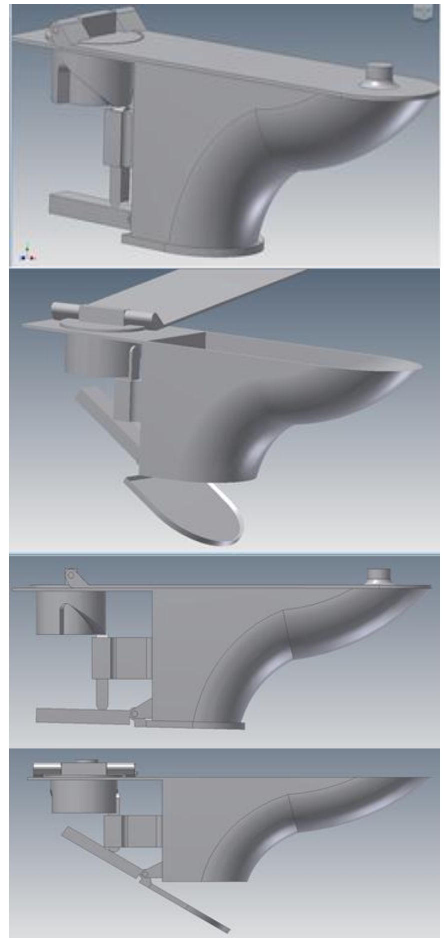

Figure 9
Cam draft in AutoCAD with areal angled view closed, areal angled view open, side view closed, side view open