Decentralized Sanitation Systems for Densely Populated Regions: Design, Prototyping, and Systems Value Analysis

by

Andrew Lee Tsang

B.S., General Engineering (2009)

Franklin W. Olin College of Engineering,

Submitted to the System Design and Management Program

in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

June 2021

Signature of Author ……………………………………………………………………………...
System Design and Management
August 22, 2019

Certified by ……………………………………………………………………………..............
Afreen Siddiqi
Research Scientist, Department of Aeronautics and Astronautics
Thesis Supervisor

Certified by ……………………………………………………………………………..............
Bryan R. Moser
Academic Director and Sr. Lecturer, System Design and Management
Thesis Supervisor

Accepted by …………………………………………………………………………..................
Joan S. Rubin
Executive Direct, System Design and Management

Decentralized Sanitation Systems for Densely Populated Regions: Design, Prototyping, and Systems Value Analysis

By

Andrew Lee Tsang

Submitted to the System Design and Management Program on August 22nd, 2019 in Partial fulfillment of the requirements for the Degree of Master of Science in Engineering and Management

ABSTRACT

Approximately 7.5 billion people live presently on earth, and 2.3 billion lack access to basic sanitation facilities such as toilets or latrines. The International Water Association estimates that 80% of all wastewater gets discharged into waterways. Untreated wastewater affects the community as easily as water flows. Toilets with septic tanks and latrines are the primary repositories for human waste today. However, the essential subsequent task of disposing that fecal sludge or septage is rarely done in a safe manner. A lack of safe, official dumping sites means this sludge and septage is discretely disposed of in water ways, pits, or drains, which affect the local health and aesthetics.

The main question posed in this thesis is "What are cost effective ways to building sanitation infrastructure in developing countries?" This thesis presents a design of a decentralized system conceptualized, prototyped, and analyzed using tools of systems engineering and systems analysis. The development of a lab-scale processor is presented in this thesis. The lab scale system processes 3.5kg of 20% sludge per hour. Using a trade space analysis, the system is compared to other methods of fecal sludge processing; a decentralized method can obtain similar health results for 15-25% of the cost per person served. A systems complexity analysis was done to compare options, and then the economic implementation was analyzed using Monte Carlo simulation. The findings suggest a decentralized model is very cost effective, but not cost effective enough to be a standalone business outside of government purchase.

Thesis Supervisor: Afreen Siddiqi
Title: Research Scientist, Department of Aeronautics and Astronautics, MIT

Thesis Supervisor: Bryan Moser
Title: Academic Director and Sr. Lecturer, System Design and Management

Table of Contents

Acknowledgements

I would like to thank:

God for the opportunity to study at this Institution and work on sanitation infrastructure.

My thesis advisors Afreen Siddiqi and Bryan Moser for their patience in editing and experience.

My project advisor and inspiration for working in sanitation Susan Murcott.

My teammates Islam Genina, Phil Dixon, Hannah Hoffmann, Danielle Gleason, Coby Unger, and Aadish Rakhecha for their dedication and work in this field.

My wife Charlene for putting up with sleepless nights.

My son Anderson for patience with my absence.

Notation and Abbreviations

OSS	Onsite sanitation system
FS	Fecal Sludge
ABR	Anaerobic Baffled Reactor
AS	Activated Sludge
FSTP	Fecal Sludge Treatment Plant
BOD	Biological Oxygen demand
COD	Chemical Oxygen Demand
Honeysucker	Vendor who uses a vacuum truck to mechanically empty a septic tank or pit latrine
eNPV	Expected Net Present Value
UASB	Upflow Anaerobic Sludge Blanket

1 Introduction:

The WHO estimates that 63% of fecal sludge in the world is not safely disposed of. Diarrheal and gastrointestinal diseases is one of the top 5 leading causes of death worldwide, with over 2,195 child deaths each day—more than the combination of AIDS, malaria, and measles. The influences of population growth, climate change, and rapid urbanization mean these issues will only grow in likelihood and severity. Even in supposed "open defecation free" communities, services that empty the pits and latrines are not sufficiently preventing the human waste from entering back into the environment. Septic trucks still lack appropriate disposal options, leading them to dump wherever convenient: rivers and lakes, pits, drains, the "backyard", etc.

In many of the most at-risk communities, a modern sewage system with centralized processing facility is quite out of reach. Therefore, development strategists turn to decentralized fecal sludge treatment solutions for areas that do not have sewered systems. The goal is to leverage the current network of latrines and human waste "collectors", and tackle the problem of the final processing of the fecal sludge. The incremental gain in sanitation by solving this last step gets most of the way there to eliminating water contamination and defecation-caused illnesses. This is the focus of the thesis: fecal sludge treatment post on-site elimination and collection.

Cost, ownership and location need to be considered along with technology when providing sustainable sanitation for urban slums. Sanitation sustainability takes into consideration collection, storage, transport, and treatment of human excreta, grey water, solid waste and storm water, and the safe disposal or reuse of end products [1]. A sustainable sanitation system should be technically feasible, acceptable to users, affordable, and contribute to health improvement and environmental protection.

This thesis provides a literature review of fecal sludge processing, a design proposal for a system to process fecal sludge, and analysis and discussion of how it compares to alternative systems. The analysis consists of a trade study of solutions using different options for each step, then a system complexity analysis for fecal sludge treatment systems, followed by an economic study using Monte Carlo analysis.

2 Contemporary Sanitation Systems

Human Excreta and Fecal sludge

Urine and feces are the main components of excerta. These substances contain pathogens such as viruses (Polio, Hepatitis A), Bacteria (Salmonella, Para Typhi, V. Cholera), or Helminthic (Ascariasis, and others) [2]. Open defecation and excreta disposal in drains is common in urban slums [3]. Sanitation services reduce health risks, but unfortunately do not eliminate them. Examples of a sanitation service are pit latrines and septic tanks. These technologies are designed to let liquids percolate through the soil. Unfortunely, when these technologies are not installed and spaced correctly they will cause environmental soil and groundwater contamination. Major contaminant constituents from pit latrines are organic matter that has a high chemcial oxygen demand (COD), nutrients, and pathogens (bacteria, viruses and parasites) [4]. The following sections provde a brief overview of comtemporary sanitation systems in urban regions and discuss related public health and managemement issues.

2.1 Sanitation in urban slums

Unsanitary conditions result in diseases, illness, and low productivity. In slums, solid waste is often disposed of on refuse dumps. The effluent water from these dumps is discharged into drains that many times filter back into the slums. It is challenging to provide sanitation solutions that are accepted by populations living in urban slums. These challenges come from poor accessibility for cesspool pump and solid waste collection trucks to reach areas, no land ownership, and lack of education.[5].

2.2 Public health and consequences of poor sanitation

Vector borne diseases and bacterial infections, drinking water contamination, and reuse of contaminated waste products are public health concerns [6]. Specifically, diseases include: cholera, dysentery, diarrhea, and malaria [7]. They all tie back to poor sanitation. Contaminants leach into water sources, impacting drinking water and spreading diseases. It is no wonder that sanitation is the cornerstone of public health (WHO and UNICEF, 2010).

Urbanization and high population densities like refugee camps add additional public health issues. These issues can stem from the contamination and use of water obtained from boreholes, springs, and shallow wells. This combined with poor hygiene is the leading cause of child mortality and loss of working days in urban slums. Economic benefits of sanitation at a global level are \$7.6B per year in reduced health costs, and an additional \$3.6B from deaths averted [8].

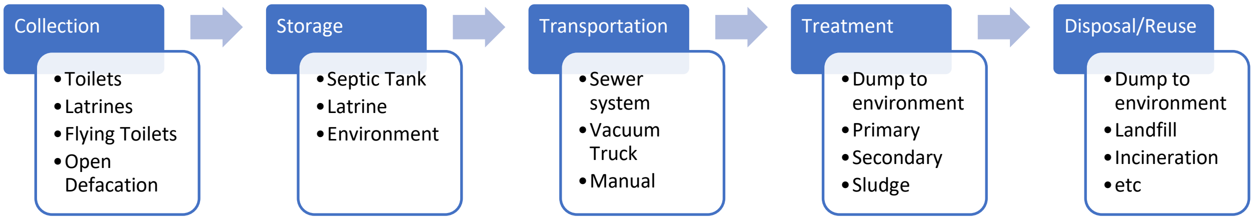


Figure 1: Sanitation Service Chain with Options

This thesis focuses on novel design and analysis for a fecal sludge management system in densely populated regions in developing countries such as urban areas or refugee camps. Fecal sludge is a product of Onsite Sanitation Systems (OSS), such as septic tanks and pit latrines. Spread across the planet, over 2.7 billion people are served by OSS, with that number expected to increase to 4.9 billion by 2030 [9]. Collection, treatment, and disposal of fecal sludge is still a challenge, with large volumes of fecal sludge being disposed directly into land and waterways such as rivers, canals, and drains [10].

2.3 Importance of Fecal Sludge Management

OSSs are a major pillar for providing access to toilets in rural and urban areas, and this is not limited to developing countries (Figure 2). Despite the significant progress towards the Sustainable Development Goals (SDGs) to increase access to improved sanitation, investments in the subsequent steps, such as the safe collection, disposal and treatment of fecal sludge from on-site sanitation systems, remain a significant challenge [11]. Lack of treatment services often results in unsafe disposal of fecal sludge.

It was estimated that USD 260 billion/year is the global cost of inadequate water supply and sanitation (WHO 2012). Compare that to the total annual capital costs of meeting the sanitation MDG, which have been estimated at USD 19.5 billion- [8]for achieving -basic sanitation and USD 49 billion- for -safe fecal waste management [12]. That is, the cost for building and providing safe sanitation is less than 8% of the costs currently incurred due to inadequate sanitation.

A compelling potential for the implementation of fecal sludge treatment plants is the ability to recover and reuse resources (RRR) from fecal sludge. RRR could provide income streams and incentivize sanitary disposal methods [13]. In a similar vein, a waste to energy for urban waste streams concept is analyzed by Haraguchi [14].Therefore, instead of polluting the environment and creating a health hazard, fecal sludge could be part of a circular economy to benefit the environment, create jobs, and reduce waste. A circular economy is the notion that where products can be restored or repurposed, waste is minimized and economic opportunities are generated sustainably [15].

2.4 Sanitation Service Chain

These processes are referred to as the 'sanitation service delivery chain' and are used as a framework for analyzing the physical flow of FS in a system [16].

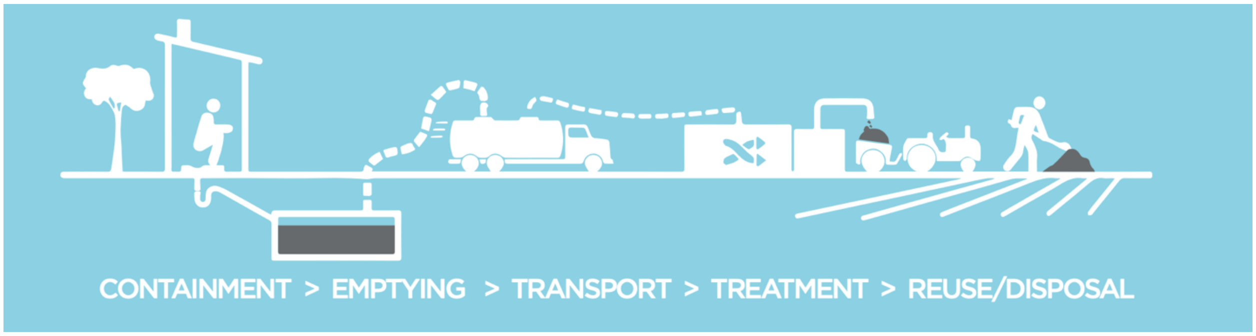


Figure 2: Sanitation Service Chain – (Bill and Melinda Gates Foundation)

- Emptying and transport: When septic tanks and pit latrines fill up, the sludge needs to be emptied and transported to a treatment site.
- Treatment: FS is collected so that it does not contaminate the environment and harm people.
- Disposal: Placement of non-useful components of treated sludge in an isolated location to reduce human and environmental contact.
- Reuse: Working with FS nutrients, energy, and water, to offer resources to a treatment plant and community.

2.4.1 Reuse of Fecal Sludge

The water-retention capacity of soil can be improved by applying human excreta. In addition, it will aid in plant growth [17] . Composting is a safe way to recover organic matter and nutrients from FS. Unfortunately, the urbanized world has caused a disconnect between excreta-generating centers and food production areas. FS contains a high concentration of organic carbon and energy that can be converted into heat and/or electricity. Techniques used to recover energy include anaerobic digestion, gasification, pyrolysis, syngas and biochar, and incineration [18].

2.5 Onsite versus Offsite Sanitation

2.5.1 Offsite sanitation

In this thesis, sewage is defined as the combination of excreta and grey water. It can be collected and transported by a pipe network to ponds for treatment before being released into the environment. After a sewer network and a wastewater treatment unit are in place, a simplified sewerage system can be used for densely populated urban settlements[19]. A simplified sewerage system is different from conventional sewerage because it has smaller elements, which decrease cost, without compromising the design principles [20] . Cost savings make simplified sewerage systems a great alternative for urban slums (Paterson et al., 2007). These systems have been implemented in Pakistan, Sri Lanka, Brazil, Colombia, Peru, Bolivia and South Africa (Bakalian et al., 1994). However, for the system to be sustainable, it has been found that communities will need to be involved in their implementation, maintenance, and operation (Mara, 2003).

2.5.2 Onsite Sanitation

On site sanitation is a solution for places where the population density is not high. For example, in the Imvepi refugee camp in Uganda, groups of four people are allocated approximately a 10m by 10m plot of land for shelter and living. The land area is large enough for the population to each construct an outhouse using local materials such as wood, mud, and tarp. When the pit is full, the location of the outhouse is moved.

2.6 Existing Sanitation in underserved communities

2.6.1 Pit latrines

Pit latrines are perhaps the most common form of ad-hoc waste capture in the developing world. The construction of the pit latrines takes time and initially lags the demand for usage. Concrete rings must be cast, sourced, moved into place, then assembled for the pit. Until sufficient pit latrines are formally constructed, and processing facilities are created, pit latrines are dug, and when full, capped, and a new one created [21]. The recommended guideline for a pit latrine is one for 20 people, but in the beginning of an emergency situation, that number can exceed one pit latrine for 200 people, as in the case of refugee camps.

Refugee camps and urban slums arise either as a reaction to an influx of people or in anticipation of the influx. The sudden arrival of many people into one area strains existing infrastructure and resource allocations, creating an underserved urban community. On average, the lifespan of a refugee camp is 17 years [22], but the planning can be difficult to project. In most cases, the refugee camp is planned to be temporary, with minimal allowance for ‘permanent’ infrastructure [23], which would be objects buried in the ground such as foundations and underground pipes.

Depending on the ground water conditions, the pits may have a water permeable or impermeable bottom. Once the pit latrine is full, the contents need to be emptied to prevent the sludge from entering the environment. In the case of the Kutupalong refugee camp in Bangladesh, one particular camp of 20,000 uses about 0.4L of sludge per day at roughly 2% solid. The pits were typically excavated by a portable gasoline powered pump into 40L or 60L barrels, which were then transported by two people to a central processing location. Due to the hilly nature of the land, sometimes the gasoline powered pump was unable to be brought to the latrine, so emptying was done using a bucket attached to a rope. [23]

2.6.2 Container based sanitation

Some more recent innovations fall under the category of container-based sanitation. The main idea is to safely contain the human waste at the point of defecation and urination so the transportation can be done safely and easily. Typically, urine is diverted and the solids are collected and stabilized with biomass such as sawdust. Lab research being conducted by an example company like Change Water Labs involves a polymer which dewaters the mixed urine and feces, which leaves only the solids with minimal mass. In these methods, the polymer dried waste does still need to be collected and safely processed.

Another example would be Sanergy [24], which turns the waste to animal feed, fertilizer, and some syngas through anaerobic digestion. Sanivation takes the feces and mixes it with biomass and a binder to produce an alternative to a charcoal briquet. Change Water Labs[25] is producing a toilet which utilizes the polymer to dewater the human waste to ease transportation.

2.6.3 Locally made retention ponds

Once the fecal sludge is collected, it should be treated to eliminate pathogens, reduce BOD and COD and any other potentially harmful substances. The treatment done at the International Redcross camp within the Kutupalong camp consisted of mixing lime with the wastewater to bring the pH to a suitable level. The mixed waste water was allowed to soak for at least two hours with the pH level confirmed at the end of soak. Then the mixture was poured into retention ponds to dry. The retention ponds were engineered with gravel beds to allow percolation of the water into the soil below while the sludge can dry under atmospheric conditions. Due to the rain in Bangladesh, semitransparent tarp covers were created to shield the drying sludge from water. After approximately two weeks, the sludge is dry enough to be removed by shoveling and then placed into a covered area for 30 days to further decompose. The remaining material is then used for fertilizer or soil amendment. The amount of lime consumed is approximately 0.1kg/L of waste water treated [21]. Retention ponds are also common in semi urban places where the fecal sludge can be transported to a more remote location with space away from living areas [23].

2.6.4 Anaerobic Lagoon for biogas production

An anaerobic lagoon is a type of sludge treatment which places the fecal sludge into an airtight environment to allows anaerobic bacteria to break down the fecal matter into carbon dioxide and methane. These environments are typically constructed with earth and are not heated, aerated, or mixed [26]. Within the same refugee camp, a large anaerobic digestion pond is being created to serve 150,000 people with a capacity of 40 cubic meters of sludge per day. The large ponds are approximately 5 meters deep, 40 meters across, and 80 meters long. The capital expenditure cost 150,000 British pounds for construction. The design of the facility means the sludge is pumped into one retention pond until that pond is full. That pond is then capped with a gas impermeable tarp containing collection pipes for the syngas generated. When one pond is filled, the next pond is used for new material while the sludge degrades anaerobically in the first pond [23][27].

2.6.5 Truck to local treatment plant

Other options for refugee camps are offsite treatment and disposal, where the sludge is removed by vacuum truck to a local treatment plant. One example of this method is in Greece, where the refugee camps house approximately 20,000 and have portable shelters for housing and toilets.

However, for many refugee camps, no available treatment plants are in the area [28]. In urban areas where a treatment plant is nearby and operational, the waste collectors can use that as an option.

2.7 Contemporary Solutions Conclusion

Along the sanitation value chain, various methods exist to transport, treat, dispose, and reuse fecal waste. The solutions for treatment and disposal, and reuse are typically site specific, whether it is lagoons for biogas or retention ponds. The next chapter discusses the design of an integrated system to process fecal sludge across different contexts.

3 Development of an Integrated Fecal Sludge Treatment System Introduction

The area of fecal sludge management of great importance for the global community to achieve the Sustainable Development Goals of achieving access to sanitation and hygiene (6.2), elimination of dumping (6.3), and expanding capacity building (6.A). There are numerous fecal sludge treatment methods and systems developed over the past century. Many of which are capital, resource and land intensive, in addition to their requirement of skilled labor and pre-existing infrastructure. The four main pillars of the sanitation value chains can consist of several systems with variable out comes. When a practitioner, who may be an engineer or a planner or any other key stakeholder, has to design an integrated fecal sludge management system, the boundary conditions and input parameters are usually as follows:

Pre-existing infrastructure, which consists of roads, onsite containment systems, land availability, energy and water availability

Capital, or funding for sanitation services in capital and operating expenses

Wastewater/Septage Characteristics: Total Solids, Chemical Oxygen Demand, fecal coliform, nitrogen, phosphorus

User Data: Number of users, fecal sludge generation rates, socio-economic status

Treatment goals for the end use of processed sludge and disposal of effluent water

3.1 Designing with the Enduse in Mind: a Sytems Level Approach

When designing an integrated fecal sludge management plan, one should determine the goals and objectives of the treatment. It is therefore useful to scope the design and base it on some boundary conditions. Such conditions could range from the need to convert fecal sludge into compost or charcoal briquettes, to the need of safely managed fecal sludge treatment with the minimal possible cost. Determining this end goal will help the designer deal with the various operational values that impact the variability of the fecal sludge, and hence, the treatment methods. The end go al of fecal sludge management and treatment should be resource recovery. This can help off-set part of the costs associated with collection, transportation and treatment of sludge and could potentially incentivize stakeholders, from a financial standpoint, to be part of the FSM plan. From a sanitation perspective, a good solution would need to address the entire value chain: collection, storage, transportation, treatment, and disposal or reuse. The solution also needs to meet the needs and capabilities of the community, meaning operation and maintenance must be considered [29].

From the system level perspective, designing an FSM plan requires a deep understanding of stakeholders and meeting their interests, knowing their boundaries, current conditions, mechanisms for financing sanitation and existing FSM systems. Understanding and integrating all those aspects together will help in designing a system that meet the targets of the end users as closely as possible

In this chapter, resource recovery is considered the target treatment ability as it will provide financial incentives to drive the sanitation service chain forward. With increased financial incentive at the end-use level, the financial burden at the level of fecal sludge collection from households will decrease, improving livelihoods by increasing access to improved sanitation services and decreasing exposure to pathogens.

The sanitation system developed in this chapter aims at converting fecal sludge into energy, a valuable resource in many communities. When such resource has a high market demand, fecal sludge treatment plants (FSTP) will charge lower tipping fees from FS collection and transportation workers to discharge their FS at proper treatment locations, instead of directly dumping it into the environment.

In this chapter, the sanitation value chain will be presented as five main pillars:

1. U: User interface
2. S: Storage and Containment
3. C: Conveyance
4. T: Treatment
5. D: Disposal or reuse

These pillars differ slightly from the value chain presented in Figure 2 from the Bill and Melinda Gates Foundation, which focus on Containment, Emptying, Transport, Treatment, and Reuse/Disposal. The five main pillars discussed above include the user interface as a component of the sanitation system because different user interfaces have health and cleanliness implications.

3.2 User Interface systems: toilets

In the context of peri-urban sanitation, the most commonly used toilets are:

U.1: Dry Toilet; where the user gets to squat in order to use the toilet. This setting is very low in cost and does not require water for flushing. However, dry toilets have problems of smell and visibility of the pile of fecal matter, in addition to the presence of flies, which are disease vectors.

U.2: Urine-Diverting-Dry Toilets; Similar to dry toilet, but can separate the urine away from the feces, which reduces the problems of flies and odors if built and maintained adequately.

U.3: Pour Flush Toilet; where water is used to flush the excreta past the S-shaped water seal. This prevents flies and odor from returning backwards through the pipes. There is no pile up of excreta due to continuous flushing. However, the downside is that it requires a supply of water for the flushing.

U.4: Cistern Flush Toilet; similar to the pour flush toilet, with a water tank up-top that releases water at high flow rate to carry away the excreta. The S-shaped water seal is more sophisticated and hence, more effective at preventing flies and odors. The downsides include its high capital cost and difficulty being built and repaired from locally available materials.

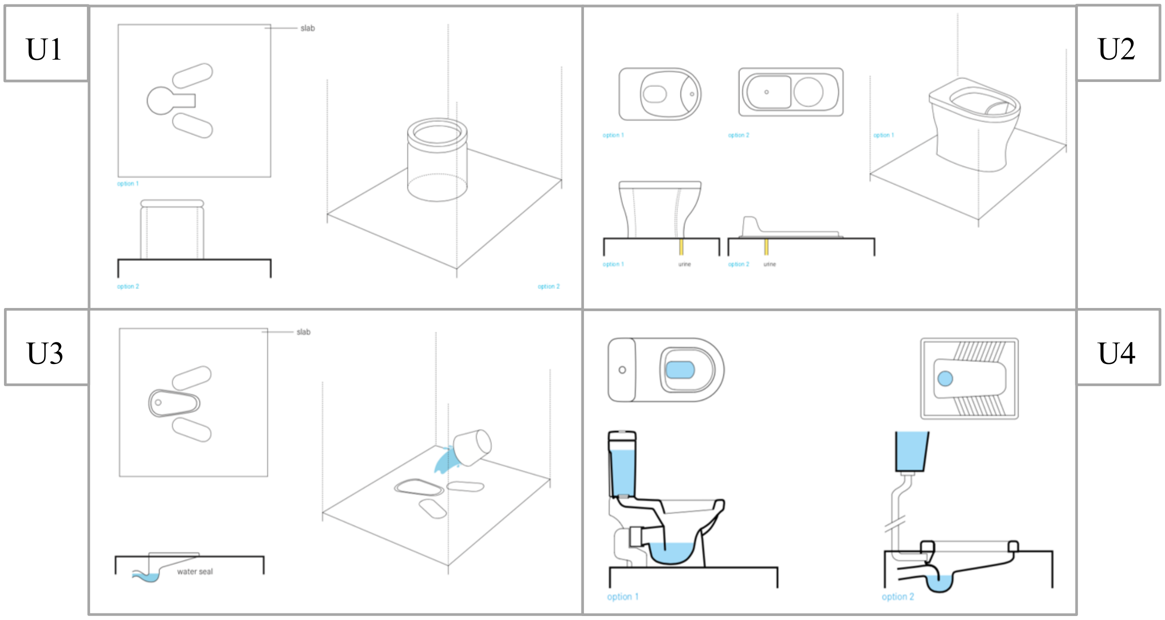


Figure 3 Showing schematics of the various types of toilets commonly used in low-income communities. U1 is a dry toilet. U2 is a urine-diverting dry toilet – figure compiled from Compendium of Sanitation Systems and Technologies (eawag)

3.3 Methods of Fecal Sludge Containment:

S.1. Single Pits:

The single pit is one of the most widely used sanitation technologies. The single pit is one of the most widely used sanitation technologies. Excreta, along with anal cleansing materials (water or solids) are deposited into a pit. Lining the pit with concrete or brick prevents it from collapsing and provides support to the superstructure.

As the single pit fills, two processes limit the rate of accumulation: leaching and degradation. Urine and water percolate into the soil through the bottom of the pit and wall, while microbial action degrades part of the organic fraction. A single pit is an improvement to open defecation; however, it still poses health risks:

- Leachate can contaminate groundwater;
- Stagnant water in pits may promote insect breeding;
- Pits are susceptible to failure and/or overflowing during floods.

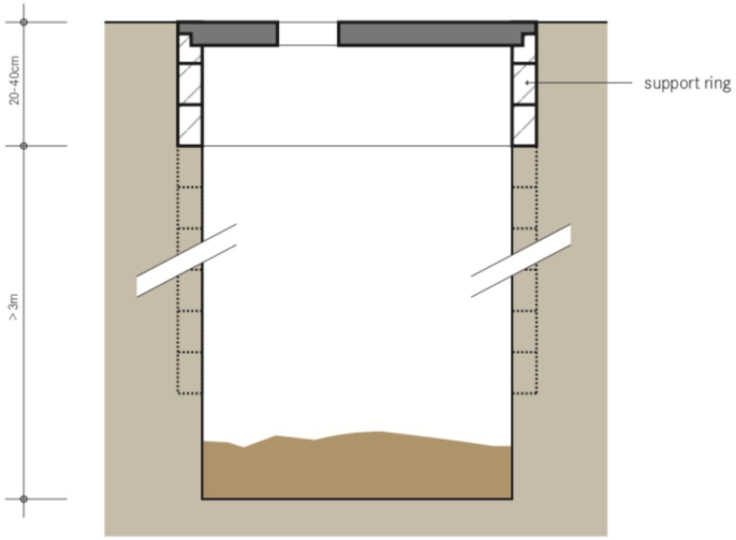


Figure 4: Septic Tank Diagram Source: Compendium of Sanitation Systems and Technologies (eawag)

S.2. Single Ventilated Improved Pit (VIP):

An improvement over the Single Pit (S.1) is the Ventilated Improved Pit (S.2). The ventilation is achieved by allowing odors and gasses to escape though a raised pipe, which also traps flies when they try to fly towards the light. The VIP has the potential to be smell free for the users and avoid insect breeding.

S3:S.3. Fossa Alterna

The Fossa Alterna is a twin pit latrine which does not use water[30]. Users alternate between pits on a short cycle and regularly cover the feces with material such as soil, ash, or leaves to help produce a safe to handle, earth-like product to condition soils while reducing flies and odors. The retention time for the excreta is recommended to be at least one year

S4: Twin Pit for Pour Flush

This type of containment is similar to the Fossa Alterna (S.3), but the alternating time is longer. There is less user involvement because water is used to maintain the odor seal since it is connected to a Pour Flush (U.4) as opposed to covering with materials. Like the Single Pit, water can slowly infiltrate into the soil, and over time, the pit not in use will be sufficiently dewatered to a state where it can be desludged with a shovel. Similar concerns to the single exist in this double pit.

S5: Composting Chamber:

The Composting chamber is similar to the (S.3) Fossa Alterna in the output it produces, and the process required. Bulking material must also be applied, and the output is a safe, stable product which can be used as a soil conditioner. Over time, the excreta and bulking material decompose under aerobic conditions into compost. Minimal flies and odors would be present, this chamber is different from (S.3) in that it is a single chamber as opposed to an alternating option.

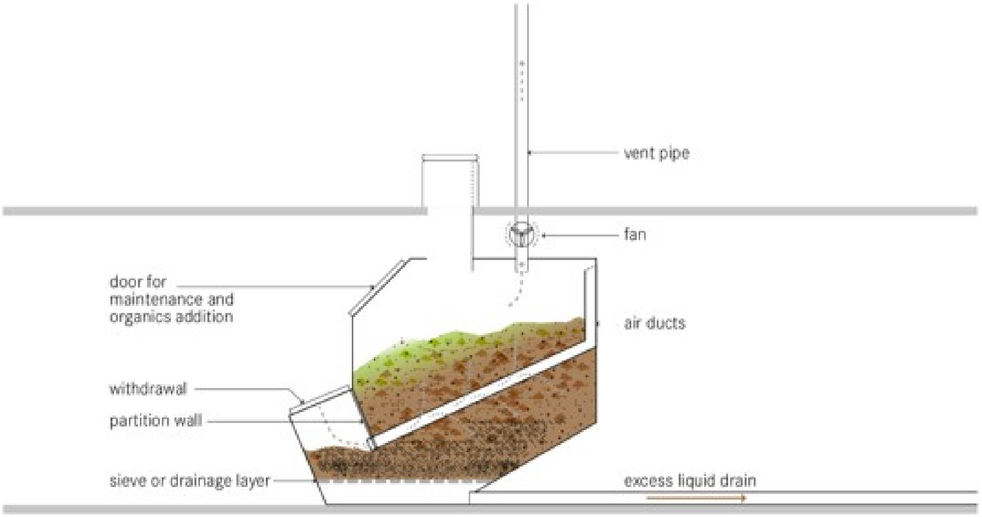


Figure 5: Composting Chamber Source: Compendium of Sanitation Systems and Technologies (eawag)

S.6. Septic Tank:

A septic tank is a form of primary water treatment where the wastewater flows into a leak free chamber to separate the solid which settle and scum which floats from the water. The tank is usually constructed from concrete, fiberglass, or PVC. The solids which settle on the bottom degrade through passive anaerobic processes which reduces the amount over time. The water should flow to a soak pit (D.7) or leach field (D.8) where it can percolate into the ground. The accumulation of solids within the chamber does occur at a higher rate than the decomposition, so septic tanks need to be desludged on a regular basis. The Septic tank can remove up to 50% of solids, 40% of BOD, and 1-log removal of E.coli, though this strongly depends on the surrounding climate and design and condition of the septic tank.

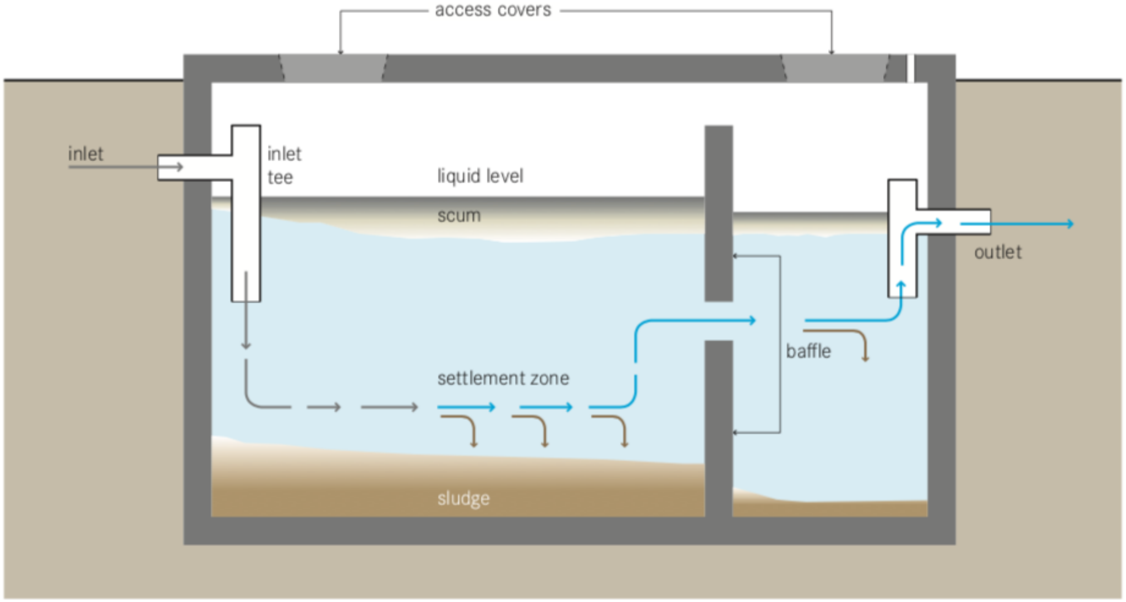


Figure 6: Septic tank Source: Compendium of Sanitation Systems and Technologies (eawag)

S7: Anaerobic Baffled Reactor (ABR) The ABR is similar to a septic tank in that it has a watertight compartment and separates the solids from liquids. The addition of baffles increases the hydraulic retention time and helps further degrade the sludge and remove up to 90% of the BOD. Similar to the septic tank, the water effluent does need further treatment or safe discharge and the system does need to be desludged periodically.

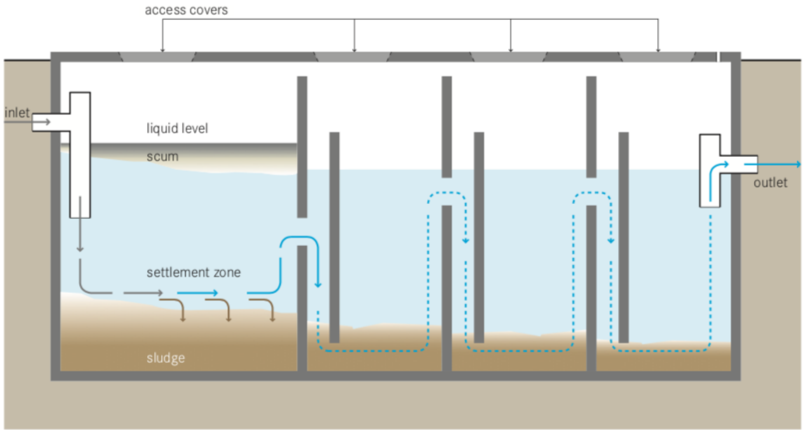


Figure 7: ABR Reactor source: Compendium of Sanitation Systems and Technologies (eawag)

S8: Biogas Reactor

A biogas reactor, also known as an anaerobic digester, is a method which takes fecal sludge or waste water and produces syngas (a combination of methane and carbon dioxide) and digestate (a slurry appropriate for land application). The reactor works by taking the wastewater or sludge and storing it in an air tight container so that an anaerobic process breaks down the organic material. The gas can be used on site for cooking or heating.

The design and operation of this reactor does require skill and the reaction is sensitive to the surrounding climate and inputs with regards to water ratio and chemicals. The digestate which exits the reactor may not be safe for human contact and may require further treatment.

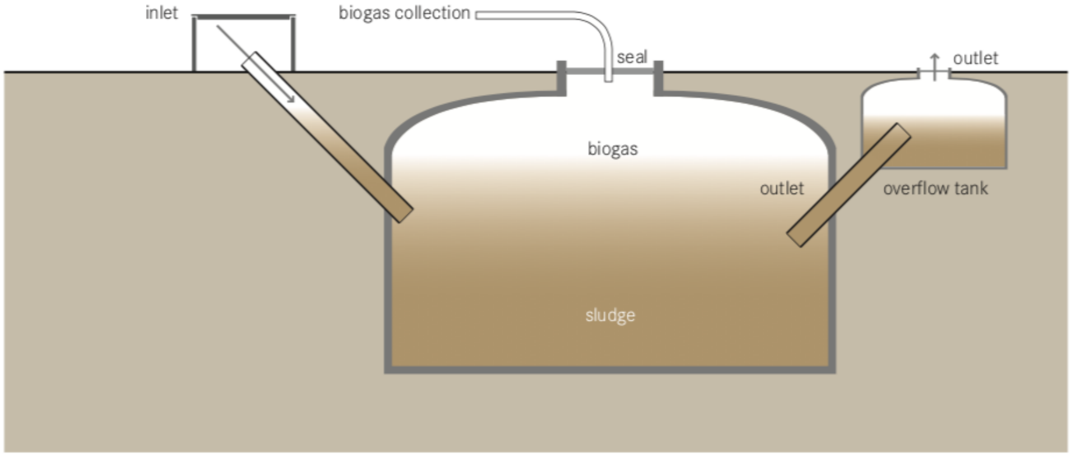


Figure 8: Biogas Reactor source: Compendium of Sanitation Systems and Technologies (eawag)

3.4 Systems for Conveyance of Fecal Sludge

For each of these conveyance systems the per capita capital cost (CAPEX) and operating cost (OPEX) in dollars and a health cost are determined. Costs for systems can vary for region to region, these numbers are compiled from Dakar and India, but can provide some relative comparison. The health cost is estimated based on the number of people and duration of contact with wastewater and fecal sludge. A higher cost (10) is associated with extended human contact with fecal sludge while a score of 3 would indicate handling in a controlled manner.

C.1. Manual Scavenging:

Manual Scavenging is a process where people are employed to empty a pit by hand or hand tools. This is done using shovels, buckets, Jerrycans or other types of lightweight containers that are locally available. While manual scavenging is low cost, it is often performed in an unsafe manner, with the worker in direct contact with fecal sludge because he is standing in the pit to dig out the sludge. Personal protective equipment is rarely worn and facilities to thoroughly wash afterwards are not common. India has recently banned manual scavenging. The containers used are ideally easy to carry and transport only when filled correctly and sealed tightly. They are ideal to transport urine, but not fecal sludge.

C.2. Human-Powered Pumps:

Human powered pumps are a safe alternative to manual scavenging, instead of the worker in direct contact with the sludge, the person uses a human powered pump or apparatus to excavate the sludge into a container. This minimizes contact with the sludge and is a solution for tight spaces where mechanized methods would not fit, such as dense urban settings or in very hilly terrain.

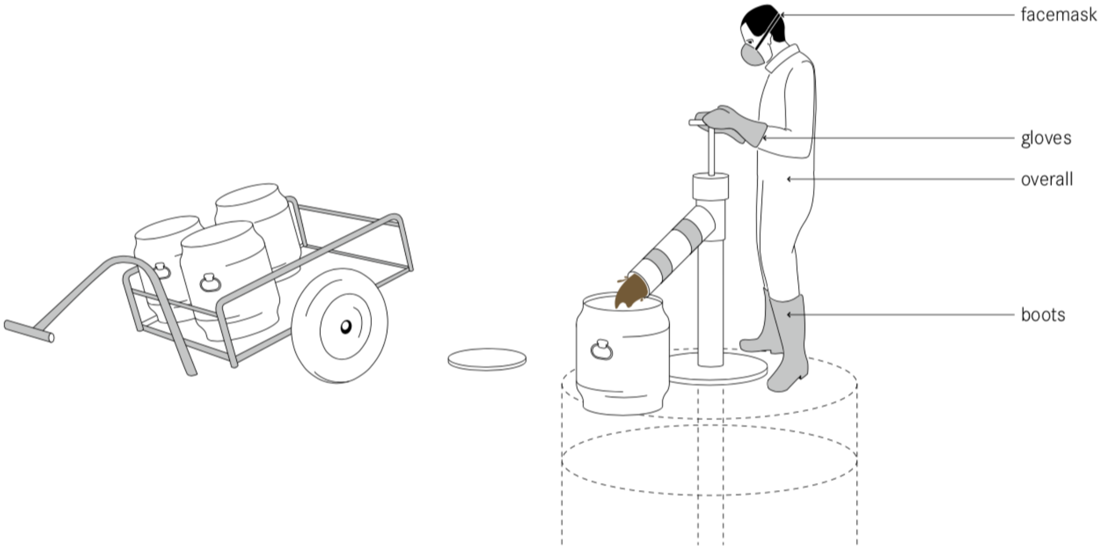


Figure 9: Human Powered Sludge Removal source: Compendium of Sanitation Systems and Technologies (eawag)

C.3. Mechanized Vehicles:

The mechanized method utilizes machines to pump the sludge or waste water out of the pits and tanks (S.9). Where possible, workers will utilize a truck equipped with a pump and storage tank. This allows them to maneuver a hose into the chamber and empty. The pump usually runs off diesel from the truck. In densely populated locations where it is difficult for a truck to get access, other mechanized means could be machines which are usually small gas engines with a pump and tank. Overall, mechanized methods offer a much safer alternative to the workers compared to manual scavenging.

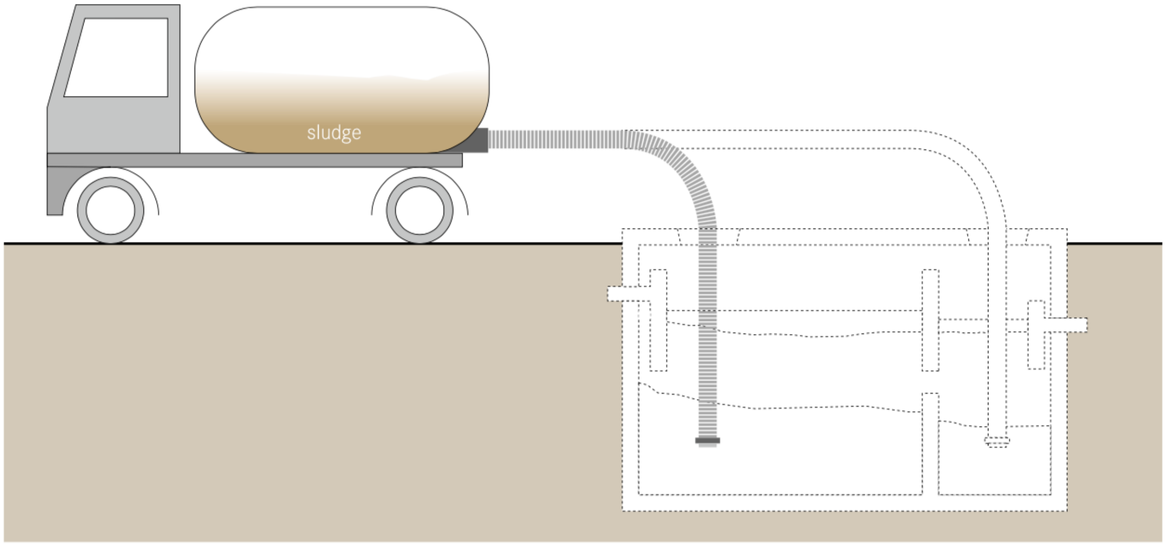


Figure 10: Mechanized Vehicles for sludge removal source: Compendium of Sanitation Systems and Technologies (eawag)

C.4. Simplified sewers:

A simplified sewer network is a series of underground pipes which convey blackwater to a central point. A simplified sewer differs from a gravity sewer in that the pipes do not carry storm water or gray water, and therefore are smaller in diameter, can be laid at shallower depths next to the road, and don’t need the steep inclines of a gravity sewer. Sometimes pumps are necessary to ensure flow, however. The storm and gray water can be transported through open channels to the waterways. Many times, these simplified sewers are used in apartment or condominium complexes within a property, so they are also known as condominium sewers. Simplified sewers can be a cost effect and healthy way to transport wastewater.

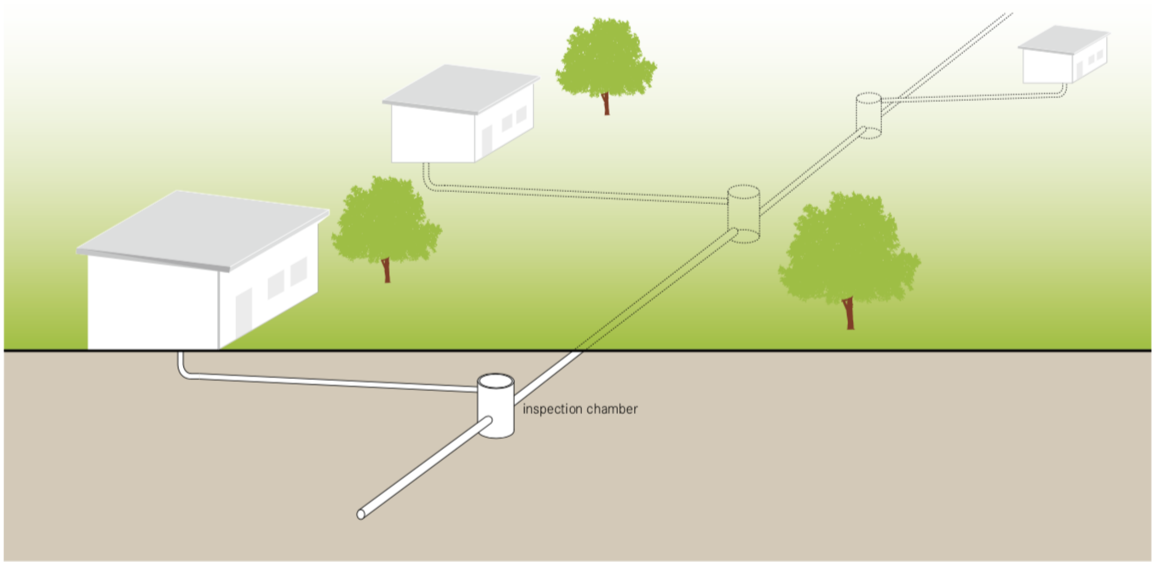


Figure 11: Simplified Sewer source: Compendium of Sanitation Systems and Technologies (eawag)

C.5. Gravity Sewers:

The gravity sewer is the typical conveyance method in 1st world cities. The sewers are formed by a large network of underground pipes to transport blackwater, graywater, and sometimes storm water to a centralized treatment facility. Typically, the gravity sewer is dug deep because they are situated under load bearing roads. The gravity sewer is designed to use the constant flow of water from households, a designated incline, and gravity to bring the water to the central facility or outflow. A sewage system usually has several main branches or arteries with smaller diameter branches further away from the center. Implementation of a gravity sewer system is extremely capital intensive, and very difficult in established cities because of the construction that must take place to lay the pipe network. From and efficiency and user perspective, a gravity sewer is very effective at separating waste from humans, provided the waste is treated appropriately. In many cities, the primary purpose of the sewer is merely to transport the waste further away for discharge to the environment.

Table 1: Conveyance Technologies

Conveyance Technologies[a]	CAPEX per person per year ($/cap/year)	OPEX per person per year ($/cap/year)	Health[b]
C.1. Manual Scavenged	0	3	10
C.2. Human Power	0	5	5
C.3. Mechanized trucks	0	5	5
C.4. Simplified Sewer	10	10	1
C.5. Gravity Sewer	20	20	1
C.6 Open Channels	5	5	8

a:Data from [31] *and* [23]

b: Estimate based on contact and spread

Table 1 is a summation of the different conveyance methods and their associated costs. Each health cost for the particular portion is evaluated on a 1-10 scale with 1 being the least costly, meaning interaction with pathogens or pollutants is minimized. Typically, higher scores are associated with being better, but in this case, a cost is assigned, so higher number is a greater cost. The health costs for each are added to generate the concept cost. For example, a conveyance method which uses manual scavenging has a health cost of 10 while a concept which uses sewers would have a health cost of 1.

3.5 Wastewater Treatment: Thickening and Settling Technologies

This section discusses Wastewater Treatment technologies related to thickening and settling (WWT.TS). The thickening and settling process is used to separate the solids from the water. For each of these wastewater treatment systems, the per capita capital cost and operating cost in dollars and a health cost are determined. Costs for systems can vary for region to region, these numbers are compiled from India, but can provide some relative comparison. The health cost is estimated based on the number of people and duration of contact with wastewater and fecal sludge. The term KLD stands for thousand liters per day, which is a standard term for the number of thousand liters of wastewater treated per day.

WWT.TS.1. Settlers:

For wastewater treatment, a setter is analogous to a septic tank where due to low velocity, solids settle to the bottom while scum rises to the top. This settling action can also remove grit, provide secondary clarification in Activated sludge treatment, and be used after coagulation steps to encourage solid particles to stick together. About 50-70% of suspended solids and 20-40% of BOD can be removed in this step.

WWT.TS.2. Anaerobic Baffled Reactor (ABR):

The ABR for wastewater treatment is similar in concept to the ABR in S.7, but at a building or municipal scale. The baffles extend hydraulic retention time, allow for more degradation of the solids and reduction of BOD compared to a settler or septic tank.

WWT.TS.3. Waste Stabilization Ponds (WSP):

Waste Stabilization Ponds have three types, but almost all are large, manmade water bodies. The different types fulfill different needs. One type is anaerobic, where primary treatment occurs. This is a deeper pond, with low oxygen levels for the bacteria to digest the solids. Up to 60% of BOD can be removed in the anaerobic pond. Typically, the outflow the anaerobic pond flows into a facultative pond, then aerobic pond, which is described below.

WWT.TS.4. Aerated Pond:

The aerated pond needs to have oxygen provided, so typically mechanical aerators move the water to provide sufficient oxygen and suspend the aerobic organisms in order to enable high rates of organic degradation and therefore pathogen removal. Aerated ponds are usually energy intensive because the mechanical mixing is electrically powered.

WWT.TS.5: Constructed Wetland:

Constructed wetlands attempt to recreate environments found in marshes, swamps, and wetlands to replicate the natural processes in those settings. Pathogens are destroyed by bacteria as the wastewater flows though while plants can utilize the nutrients. The constructed wetlands require a large land area and may facilitate mosquito breeding.

WWT.TS.6. Activated Sludge

Activated sludge utilizes microorganisms to degrade the organics present in waste water. Multiple tanks are used, one for the aerobic mixing, and one for clarification. Typically, the microorganism activity takes place in aerobic conditions and requires pumps to continually provide oxygen or surface aerators. The process utilizes electricity and pumping mechanisms, requiring skilled staff and continuous monitoring.

WWT.TS.7: Direct Dumping

Dumping to the open environment is a solution for getting rid of the wastewater from households. Typically, sewers or waste collectors will evacuate into water ways, fields, or remote areas to dispose of the waste. This solution has many adverse health and environmental effects, but is the default for places without waste water and fecal sludge treatment options.

WWT.TS.8. No Wastewater Treatment

Some municipalities only have fecal sludge treatment, household waste water from washing and cleaning goes directly into water ways.

Table 2: Wastewater CAPEX, OPEX, Land, and Health

Wastewater Treatment Technology[a]	**Capex/ KLD**	**Opex/ KLD**	**Land/ KLD**	**Health**[d]
WWT.TS.1. Settler	4000	1000	108	2
WWT.TS.2. ABR	20[a]	6	5	3
WWT.TS.3. WSP	659[b]	1000	108	4
WWT.TS.4. Aerated pond	3000	1000	11[b]	3
WWT.TS.5. Constructed Wetland	24000	1000	108	1
WWT.TS.6. Activated sludge	1720[b]	1000	0.4[b]	1
WWT.TS.7. Direct Dumping	0.0	0.0	0.0	10
Only Sludge	0.0	0.0	0.0	0

a: Data obtained from [32]

b:Data obtained from [33]

c:Data obtained from [34]

d: Estimate based on contact and spread

The wastewater treatment technologies discussed are shown in Table 2.

3.6 Fecal sludge treatment: Thicking and Settling Technologies (FST.TS):

For each of these fecal sludge treatment systems, the per capita capital cost and operating cost in dollars and a health cost are determined. Costs for systems can vary for region to region, these numbers are compiled from India, but can provide some relative comparison. The health cost is estimated based on the number of people and duration of contact with wastewater and fecal sludge.

FST.TS.1 Sedimentation / Thickening Ponds

A sedimentation or thickening pond allows the sludge to dewater by letting it settle and degrade anaerobically underwater. The output is a thickened sludge which can be further processed in composting or disposal. The effluent water requires further treatment.

FST.TS.2 Unplanted Drying Beds

This process applies fecal sludge to a drying bed, the co-composts the dried sludge with municipal solids. The process is typically manual and is labor intensive with workers handling each step. Liquid effluents evaporate and percolate into the ground. Unfortunately, the liquid is not necessarily treated and can flow into ground water or adjacent water bodies.

FST.TS.3 Biogas

Raw sludge can be converted into biogas using a sealed chamber which allows the organic matter to be anaerobically digested. Retention time is typically 2-4 weeks and a biogas consisting of carbon dioxide and methane is produced. The bacteria carrying out the digestion process is sensitive to chemicals in the input sludge. The output is a biosolid which still needs to be processed for safe discharge.

FST.TS.4 Pyrolysis

Pyrolysis uses elevated temperatures to decompose the material in the controlled presence of oxygen to convert sludge to biochar. This process does not use external power. The system is comprised of several components, grit removal to separate sand and rocks from organic matter, a pasteurizer to make the material biosafe, dryer to remove most of the moisture content, pyrolizer, heat exchanger to capture waste heat, and an effluent treatment system. This system is automated and modular for easy expansion.

FST.TS.5. Direct Dumping

Dumping to the open environment is a solution for getting rid of the fecal sludge from households. Typically, waste collectors will look for water ways, storm drain, fields, or remote areas to dispose of the waste. This solution has many adverse health and environmental effects, but is the default for places without waste water and fecal sludge treatment options.

FST.TS.6 DEWATS

DEWATS utilizes anaerobic and aerobic processes to stabilize the waste then treats both the sludge and effluent. The system is gravity fed starting with an anaerobic baffled reactor. The sludge is then moved to drying beds, which is then co-composted with municipal solid waste to make it biosafe. The liquid is treated in planted gravel filters, but pathogens are only reduced.

Table 3: Sludge Treatment CAPEX, OPEX, Land, and Health

Fecal Sludge Treatment Technology[a]	Capex/KLD	Opex/KLD	Land/KLD	Health[b]
FST.TS.1. Ponds	5000	1000	500	4
FST.TS.2. Drying Beds	6403	1600	225	3
FST.TS.3. Biogas	15000	384	12	2
FST.TS.4 Pyrolysis	10000	640	4	2
FST.TS.5. Dump	0	0	0	10
FST.TS.6 DEWATS	15937	1423	108	1

a: Data obtained from [32]

b: Estimate based on contact and spread

The fecal sludge treatment technologies are summarized in Table 3. For health scores, a treatment which is partially mechanized like the drying bed is rated as having a health cost of 3, with fully mechanized incineration 2, and dumping into the open environment 10. In these cases, the treatment has some health risk to the workers; the drying bed usually utilizes people handling the sludge, and the incineration has workers interacting with the waste collectors to transfer the sludge to the machine. The health scores for each category are added to generate a concept health score.

3.7 Morphological matrix

A morphological matrix is a graphical representation showing the different options for each architectural decision. In the case of fecal sludge treatment, the key decisions are 1. Processing capability measured in L/day 2. The conveyance method from citizen to treatment plant 3. The waste water treatment method 4. Sludge treatment method 5. Water post treatment method and 6. End use of the sludge. The morphological matrix below shows the different options considered for the transportation, wastewater treatment, sludge treatment, tertiary treatment, and sludge disposal. Combining different options leads to different architectures, thus affecting cost and capability.

Table 4: Morphological Matrix for Trade space

	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**	**Option 7**
L of Sludge per day	1200	5000	10000	20000			
Conveyance	Open Channels	Simplified Sewer	Gravity Sewer	Mechanized	Human Powered	Manual Scavenged	
WW Treatment	Settler	ABR	WSP	Aerated Pond	Constructed wetland	Activated sludge	Dump
Sludge Treatment	Ponds	Drying Beds	Biogas	Incineration	Dump	DEWATS	
Post Treatment	Tertiary Filtration	None					
Sludge End Use	Fill/cover	Leach Field	Fish pond	Water Disposal	Surface disposal		

3.8 Conclusion

Different systems can be assembled according to options selected for each stage. Those options each have an associated cost and performance. The combinations of those options generate an architecture which is explored in the next chapter.

4 Trade study of solutions

4.1 Overview

A trade space was created to explore the morphological matrix listed in Table 4. The trade space iterates over options listed in the table by multiplying the number of choices for each option by category (L Sludge per day, Conveyance, to achieve the full permutation of 10,080 possible architectures. A MATLAB script was used to conduct iterations and the resulting combinations were exported to excel for final calculations.

Figure 13: Focus of system

This analysis focuses on the Emptying/Transport, Treatment, and reuse/disposal of fecal sludge and to a lesser extent, wastewater in the sanitation value chain, shown in Figure 13. The output of the calculations is plotted using heath versus cost per person per year to graphically represent the different architectures and their benefits.

4.2 Costs

The sanitation value chain being addressed is the conveyance method for the fecal sludge/wastewater, treatment (which can be broken into primary, secondary, tertiary, and sludge), and the reuse or disposal of the waste streams. The data were gathered from compendiums and literature, and estimates were used based on similar technology if the costs could not be identified. The cost of each component is scaled for the size the system in liters of sludge per day. The assumption is 0.5L of sludge per day per person or 50L of wastewater per day per person[23]. Conveyance and emptying

Conveyance is the moving from collection point to processing point. In most developed countries, gravity sewers are used, with simplified sewers in some areas. In many developing countries, open channels are used, where waste water and storm water is collected using gutters. Other common forms of transportation would be mechanized means using a vacuum truck or cart, human powered means with a pump or device, or manually scavenged with a shovel and buckets. Emptying and conveyance are combined for this tradespace because methods are highly intertwined. A vacuum truck has a large tank for transportation and usually a pump fitted for emptying. Sewer systems empty and convey, while manual scavenging frequently utilizes manual labor for conveyance to a dump site. For each of these, an estimated cost per person for capital, operational cost per year, and a health factor were assigned. Table 1 shows the values for capex, opex, and health.

4.2.1 Wastewater Processing

Once the fecal sludge or waste water is conveyed, treatment occurs. For waste water, the following table was created with estimates for primary and secondary treatment. The primary treatment methods for waste water considered are found in Table 2.

4.2.2 Sludge processing

For places which do waste water treatment, sludge is a typical output which needs to be disposed of. For places without sewer systems which primarily process fecal sludge from mechanized, human powered, or manually scavenged, common options are listed in the table below. The data was obtained from a compendium assembled by the Nation Institute of Urban Affairs of India in 2018 [32]. A health factor was estimated given the handling necessities of each process. The results are seen in Table 3.

4.3 Tradespace

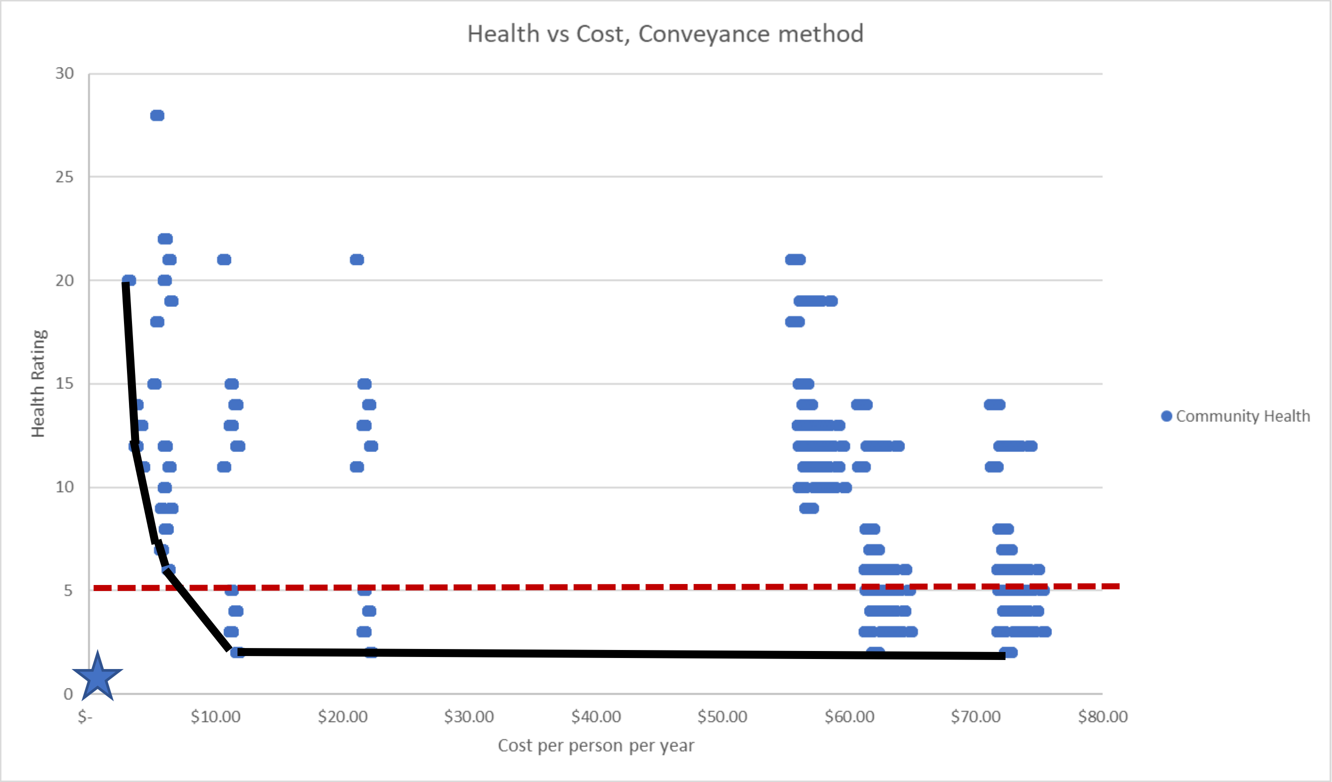


Figure 14: Tradespace exportation of health vs cost

The different options were iterated and certain unrealistic options were filtered out. Options that used human conveyance, mechanized, and human power had their outputs brought directly for sludge treatment instead of wastewater treatment. Costs for each section were either in $/person or $/capacity (1000 liters per day). For each concept, a total monetary cost for a given population was generated then divided by the number of people to arrive at a cost per person per year with the results in Figure 14. The health cost scores were added for each category as opposed to multiplying or using a maximum value to help indicate the performance as a system and allow for easier comparison. A hypothetical scenario would utilize manual scavenging with health cost (10) and waste stabilization ponds costing (4). A second hypothetical would be simplified sewers (1) to dumping into the environment (10). Neither scenario is good, multiplying would result in a health cost of 40 for scenario 1 and a health cost of 10 for scenario 2. Alternatively, addition would result in 14 and 11 respectively. The health cost using addition indicates a better similarity among bad choices so that dominating effects do not overshadow other architectures which are also not acceptable.

For terms of monetary cost vs health, many affordable options exist which are not as community health friendly. On the pareto front are three concepts which utilize manual scavenging, mechanized, and simplified sewers. Any points where the health axis is above a 5 indicates increasing risk of potential for human interaction with unsafe fecal sludge.

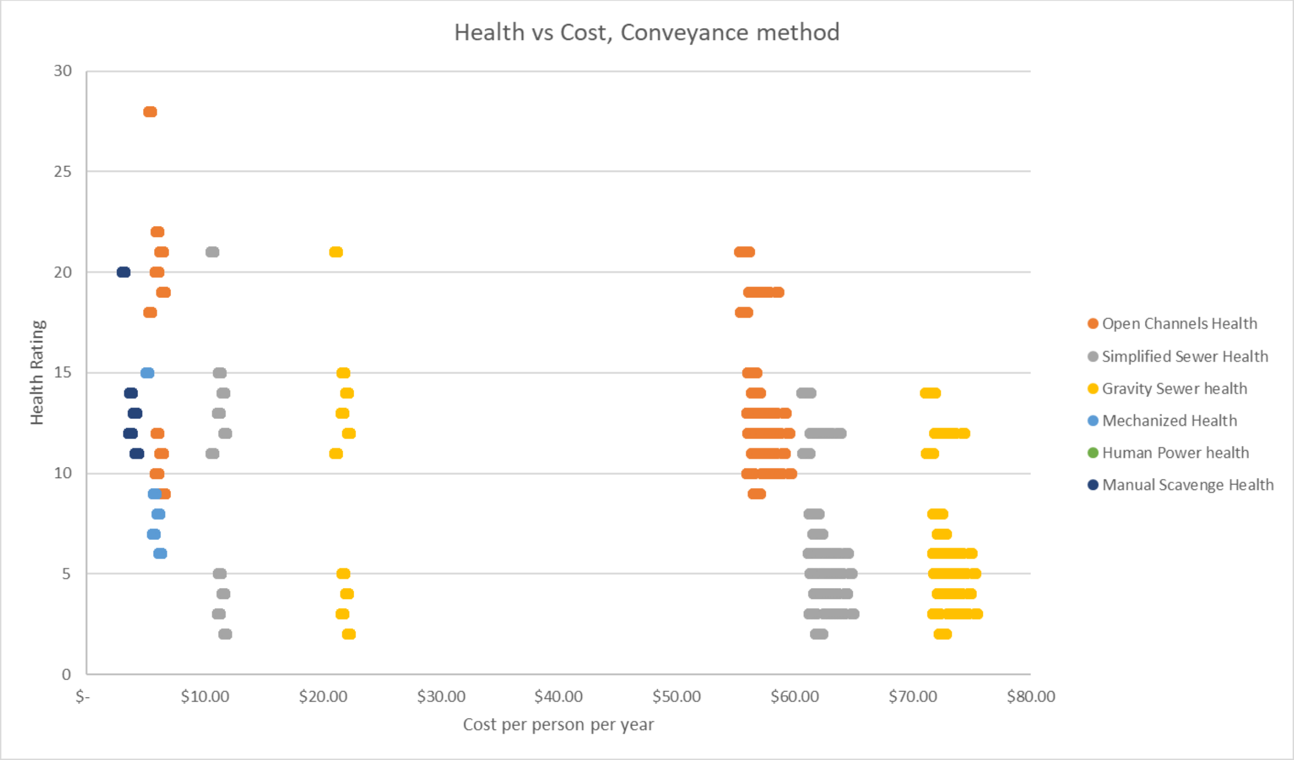


Figure 15: Trade space colored by conveyance

This chart view of conveyance method shows the effect of conveyance method on community health. At a cost of less than $10/person/year, it makes sense mechanized, human powered, and manually scavenged architectures dominate the affordable end of the pareto frontier shown in black. Minimal capital costs are required in that scenario, since no sewage system is necessary, and processing does not exist. In particular, methods of transportation which require dedicated infrastructure such as sewers are several times more expensive than on demand solutions such as a mechanized truck. In [31], Strande finds the total annualized sewer based cost to be $54.64 per person and fecal sludge management to be $11.63 per person in Dakar, Senegal, which is in the general vicinity of costs presented in the trade space.

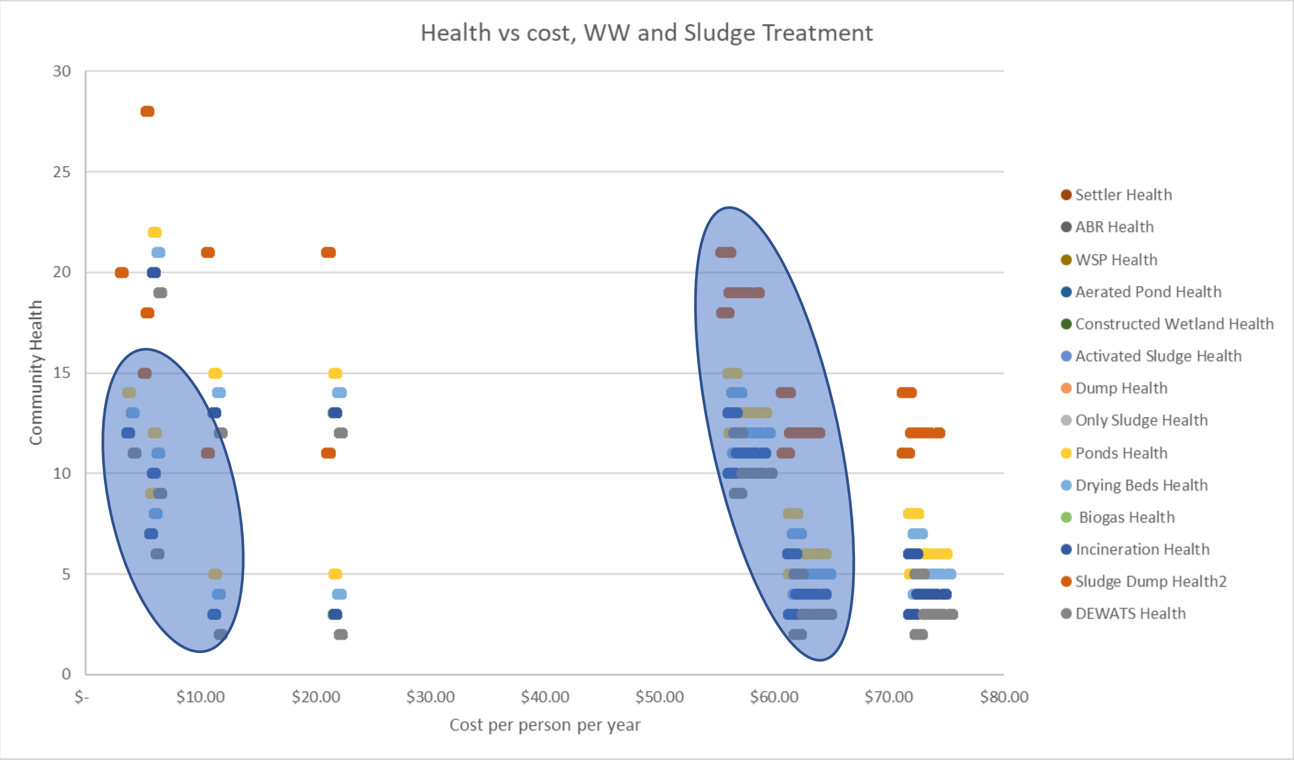


Figure 16: Trade space colored by treatment

Concepts utilizing Sludge dumping is the cheapest option. In implementation, the customer pays the waste collector to empty their septic tank or pit, and the waste collector pays no additional cost to dispose the sludge in the environment. The true cost of illegal dumping is externalized to the community in the form of degradation of community health and environment, making it difficult to quantify precisely.

An interesting region in blue on Figure 16 blue exists which is on the Pareto frontier and near the utopia point of minimal cost and low health risk. The clusters further left are Manually Scavenged, Mechanized, Open Channel, and Simplified sewer conveyance. The points iterate upwards with DEWATs, Incineration, and Drying Beds for processing. Though the open channels and simplified sewers do beneficially affect the health score, they double and quadruple the per person cost, making it difficult to implement for municipalities.

Some of the identified possibilities are shown below, with the implementation in 20, 100, 500, and 1,500,KLD sizes. The clusters on the right have waste water treatment in addition to the sludge treatment for the waste water plant output. Due to the sheer amount of water being processed, the costs are much higher, but correlate to real world numbers from Strande.

4.4 Conclusion

For cost effective solutions which can serve large populations, a centralized gravity or simplified sewage system is costly; a decentralized method can obtain similar health results for 15-25% of the cost per person served. In a city such as Mumbai, the National Environment Engineering Research Institute has proposed treating the sewage using 37 small plants as opposed to a few large ones [35]. For existing cities without sewage infrastructure nor excess capital, distributed fecal sludge treatment is a promising architecture to achieve safe processing of human fecal sludge and septage.

5 InSanirator Omni Processor description and design

5.1 System Description

An Omni Processor is a term referring to a machine which can safely process waste stream using physical, chemical, or biological treatment processes. In 2012, this term was coined by the Bill and Melinda Gates Foundation's Water, Sanitation, and Hygiene Program. Thanks to the efforts of the 'Re-Invent the Toilet Challenge' in 2012, several groups have been developing different types of Omni processors. Methods researched have included anaerobic digestion, pyrolysis, combustion, and supercritical water oxidation.

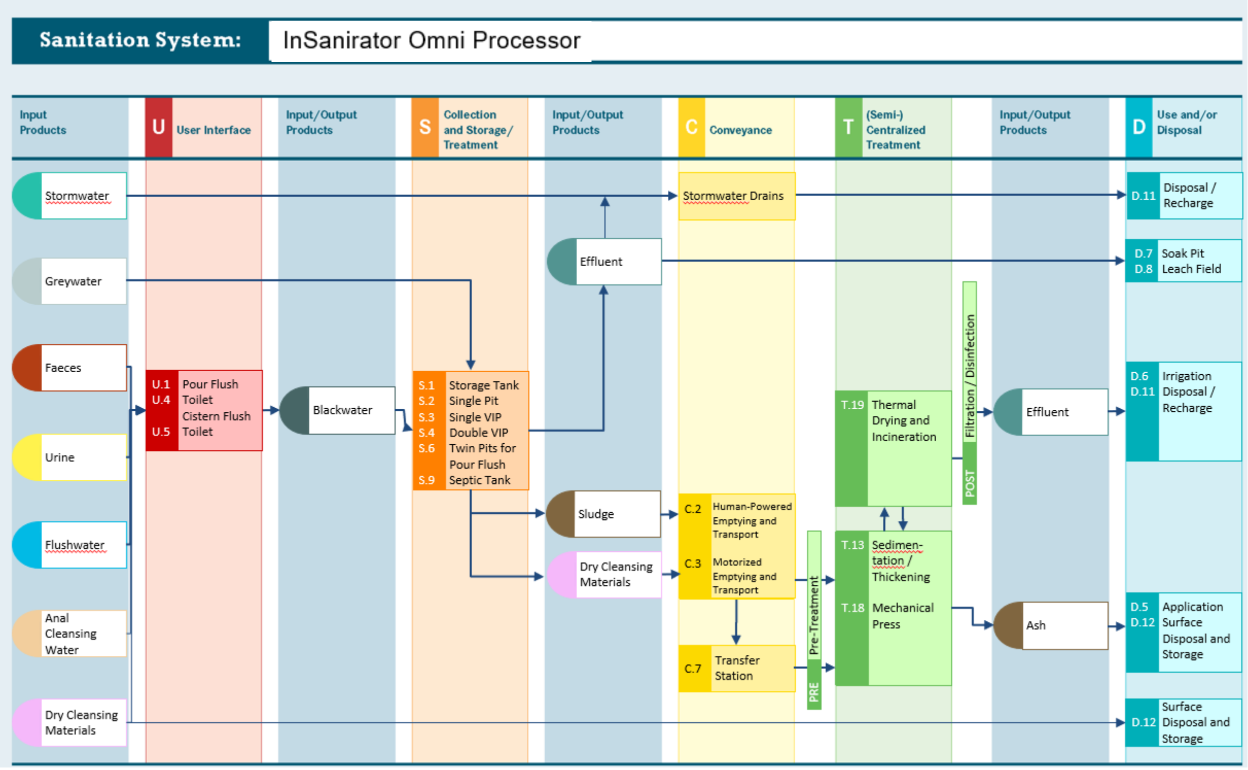
The InSanirator Omni Processor (I-OP) is a new approach which utilizes gasification of fecal sludge as its core technology. There exist two main types of gasifiers, fixed bed gasifiers and fluidized bed gasifiers. In fluidized bed gasifiers, fuel is mixed into a bed of hot fluidized sand. The bed of sand is suspended, and therefore behaves like a fluid undergoing high turbulence. This type of gasifiers is mainly used for high capacity of biomass, producing 1-50MW thermal energy and usually operate under temperatures in the range of 700-900˚C. At such temperatures, the tar produced from the thermochemical conversion process does not get cracked, therefore, it results in higher tar production and requires more air pollution control. The other type of gasifiers, fixed bed, has 3 sub-types, namely, up-draft, down-draft and cross-draft gasifiers. This type has a capacity of less than 2.5MW thermal energy and operate at a high temperature range of 800-1400˚C. Due to this high temperature, the produced tars are cracked and therefore air pollution is less of a problem.

The system takes in fecal sludge, allows it to settle for 24 hours, pasteurizes it to 80C for 30s, then mechanically dewaters the sludge to approximately 20% solid content. This 20% solid cake is then thermally dried until the waste is 60% solids content, where it is usable as a fuel source. In this fuel state, the pathogens have been destroyed. An accumulator is used to store the fuel, which is fed into a gasifier. In the gasifier, the material is heated until it off gasses, and the syngas is burned further downstream. The hot exhaust air then is fed through heat exchangers to bring the air under its condensation point. The heat exchangers are used to heat a fluid and incoming air for combustion. The fluid is fed into a drying assembly where the 20% solid sludge is dried. These components were chosen to produce a robust, self-sustaining system which requires minimal operator input. The materials the processes were selected to maximize robustness and minimize complex maintenance. Optionally, electricity can be generated by using the hot air to run a turbine or Stirling engine. Outputs of this system are water, ash, and electricity.

5.2 System flow diagram

Using the framework from EAWAG, the system flow diagram for the I-OP fecal sludge treatment plant is outlined below. The system boundary for the treatment plant would be considered starting at section T; existing infrastructure for user interface (household toilets), collection and storage (pit latrines and septic tanks), and conveyance (waste collectors using vacuum trucks) would be used.

Figure 17: System Flow Diagram generated using a tool from Compendium of Sanitation Systems and Technologies (eawag)



5.3 Materials and Methods

In the following sections, the architecture and design of a decentralized fecal sludge treatment system is developed. The scope the analysis is limited to a lab scale system which can serve communities of 1000 people. Instead of a central point with underground sewage piping which conveys all the waste water to one location, several small treatment plants are located so that existing waste collectors which evacuate the pit latrines and septic tanks have an official location to dispose of the waste.

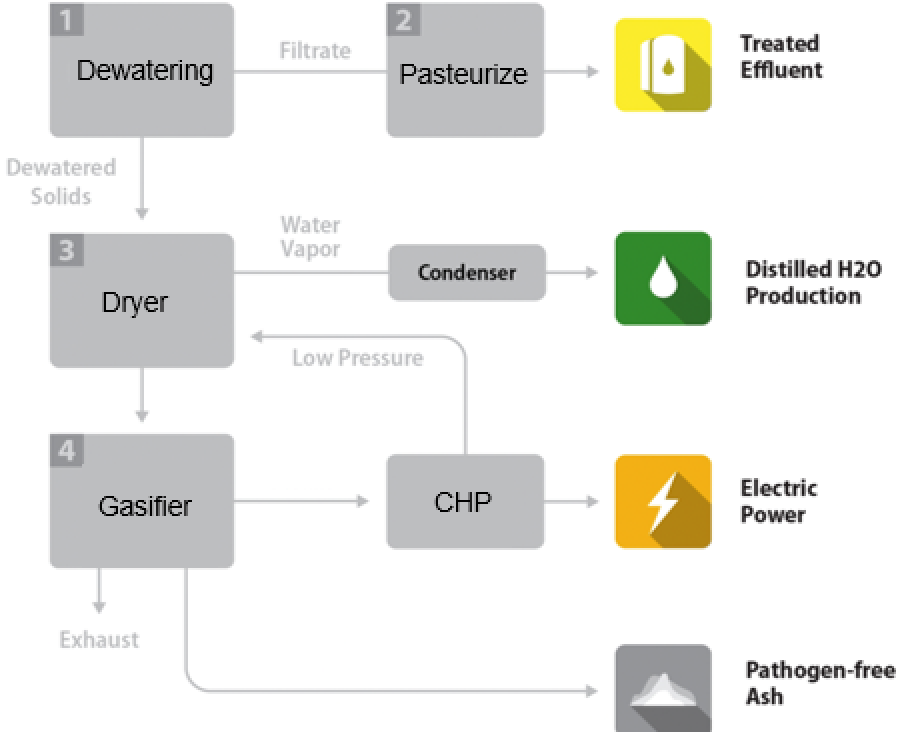


Figure 18: System flow diagram

5.4 System Design Equations and CAD modelling

The I-OP consists of three main modules. A dryer to bring the fecal sludge to the correct solids content for gasification, a gasifier, and a heat recovery portion. For the concept tests initially conducted, wood pellets were used as a replacement for fecal sludge because of its similarity in energy content. The material being dried was mashed potato prepared to 20% solid, which is the output of a rotary press. The capacity of this lab scale prototype design shown in is drying 3.5kg per hour of 20% solid material to 0.9kg of 80% solid. This prototype I-OP is designed as a proof of concept for the self-sustaining process of processing fecal sludge.

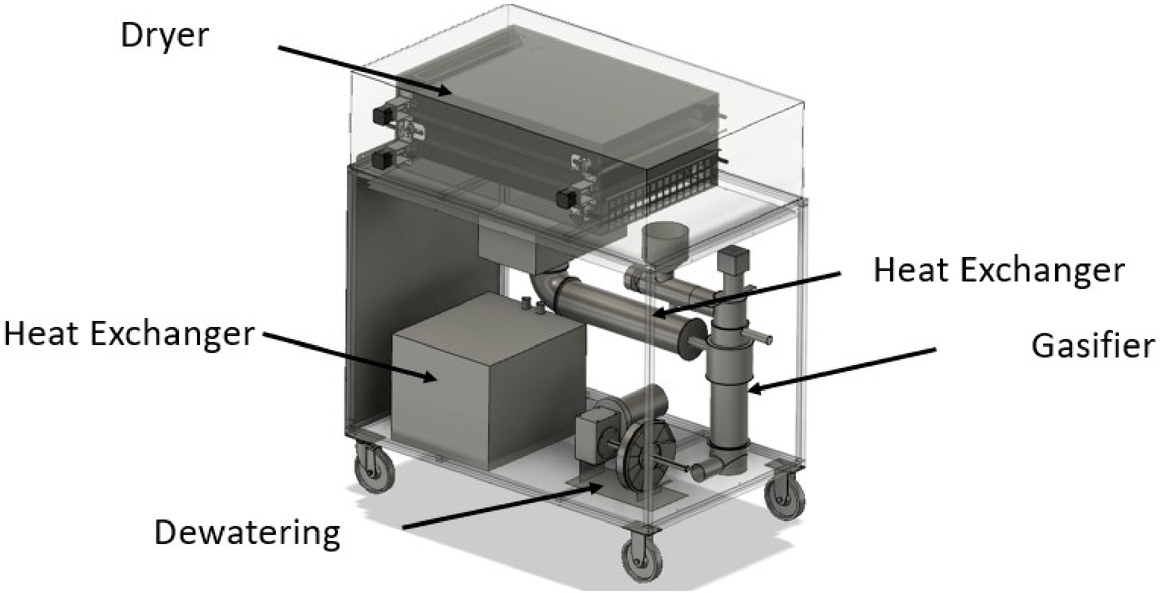


Figure 19: Rendering of lab scale prototype

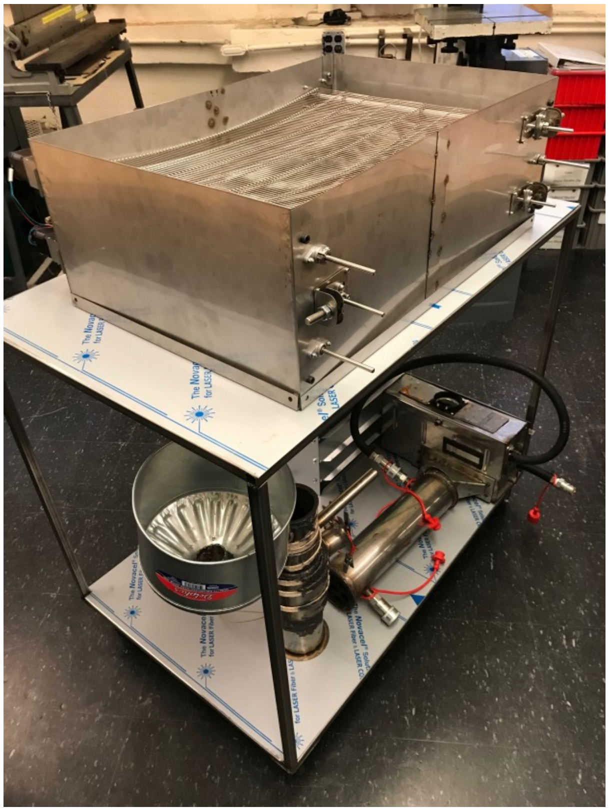


Figure 20: Fabricated Prototype

5.4.1 Gasifier

The combustion chamber has a fuel tube to hold the material during the pyrolysis process with an appropriately sized grate to allows ash to exit, air intake holes to allow oxygen containing fresh air to assist the gasification and an intake for fresh material. An overview and section view are shown in . Parameters for sizing the fuel tube are the desired mass/time unit for combustion and the appropriate heights for a drying, pyrolysis, combustion, and reduction zone.

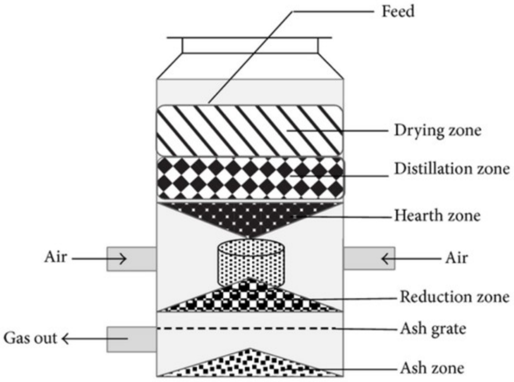


Figure 21: Gasifier and zones Source, Anukam, A

This study will focus only on the down-draft gasifier type, which is shown schematically in above in Figure 21. In the down-draft gasifier, fecal sludge pellets (sometimes referred to as biomass fuel) is fed through the top and air is introduced at an intermediate height into the combustion zone (also known as, oxidation zone). Fuel pellets move through four main zones in the gasifier before they are converted to other forms of energy and byproducts. This conversion process is referred to as thermochemical conversion, in which chemical energy is harnessed through utilizing a thermal heat to break the chemical bonds and release the energy stored within the fuel pellets. The 4 different zones of a down-draft gasifier are explained below.

Drying Zone:

Biomass fuel is fed into the gasifier top section, where it is exposed to high temperatures, in the range of 100-200˚C. This increase in temperature is due to convective and radiative heat transfer from the lower sections of the gasifier. During this process, biomass moisture content is reduced, and temperature is increased, to prepare the biomass for the next step, Pyrolysis.

Pyrolysis Zone:

As the biomass temperature increase above 250˚C, and up to 600˚C organic molecules, such as cellulose and other hydrocarbons start breaking down into medium sized volatile organic molecules and non-volatile ones (carbon char and tars). Those volatile products will flow from the pyrolysis to the hotter oxidation zone. As the medium size molecules reside longer in the hotter oxidation zone, they further breakdown into smaller molecules, such as methane, hydrogen, carbon monoxide, among others. The tars will also crack into smaller sized molecules. In the case that the oxidation zone temperature is lower than desired or the residence time of pyrolysis products is too short, the medium sized molecules will escape without being broken down further. This can result in their condensation as unwanted creosote and oils in the following low-temperature system components.

Pyrolysis is considered a key reaction as it converts the stored chemical energy in the molecules into gases, which can further be combusted or upgraded into other chemicals.

Oxidation Zone:

A zone of burning combustion (or oxidation) is formed where air is introduced into the gasifier body. This is where oxygen combines with a portion of the hot-volatilized hydrocarbons, resulting in highly exothermic reactions. Where temperatures can reach up to 1400˚C. A portion of the vast amount of heat energy generated here is transferred via convection and radiation to the pyrolysis and drying zones upstream. This generation and transport of heat energy is the main driver sustaining the pyrolysis reactions. Oxidation zone products, glowing char (unconverted carbon) and gases generated from the breakdown of medium sized pyrolysis products, proceed downwards into the reduction zone.

In order to 1. sustain a high temperature in the oxidation zone, 2. convert all condensable products from pyrolysis, and 3. avoid cold spots in oxidation zone, several measures are taken into consideration during the reactor design. Air nozzles are spread over the circumference of the same cross-sectional plane at the top of the oxidation zone. The nozzles are oriented at a 30˚ angle from the positive x-direction and another 30˚ angle from positive y-direction. This orientation creates a downward cyclonic motion of the air entering the reactor, which ensures proper mixing and prevents backflow. Air inlet velocities and reactor geometries are also well chosen.

Reduction Zone:

In the reduction zone, the products of the oxidation zone (glowing charcoal and hot gasses) are converted into producer gas. The resulting products of the reduction zone are a combustible gas and ash in the form of dust. The ash does need to be removed and is done through an agitator which attaches to a motor and rotates based on feedback of airflow.

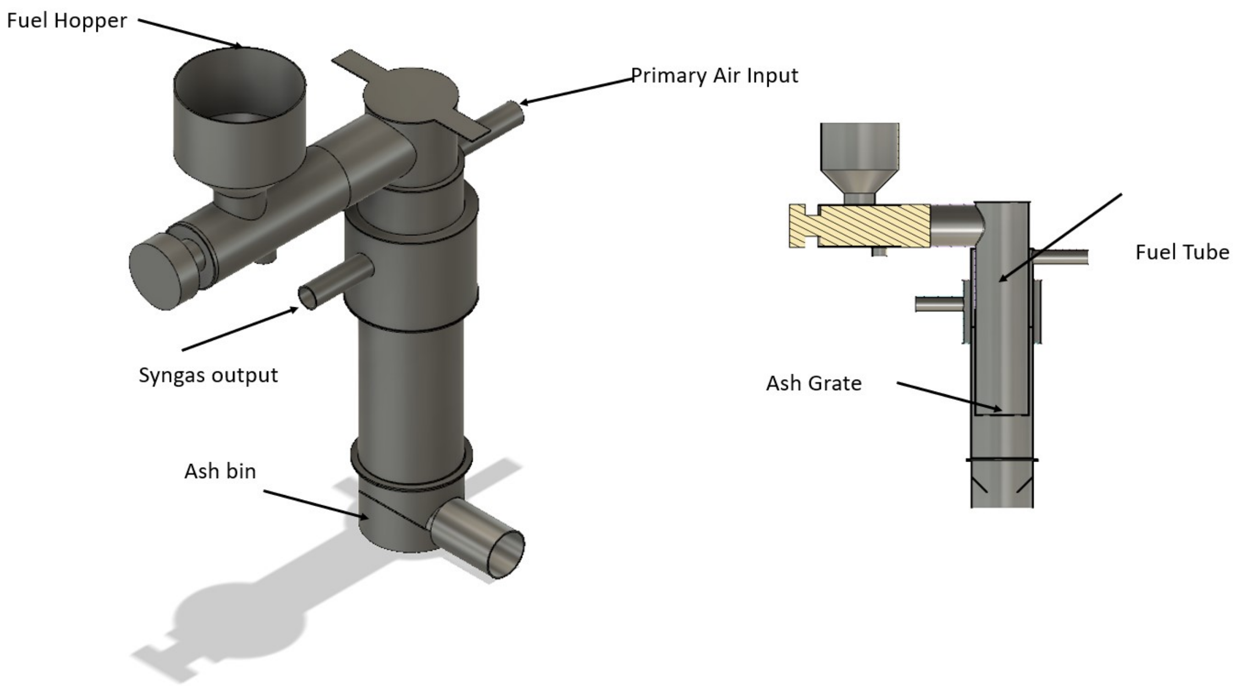


Figure 22: Combustion unit and fuel tube

Figure 23: Constructed Gasifier

5.4.2 Heat exchanger

The heat exchanger portion occurs in two separate stages. The first heat exchanger is a shell and tube to run the working fluid in a counter current to the hot exhaust air. This heat exchanger is made from stainless steel to deal with the high heat from the exhaust gas and the working fluid. A second stage is added preheat air entering the drying module. The secondary heat exchanger is also made of stainless steel.

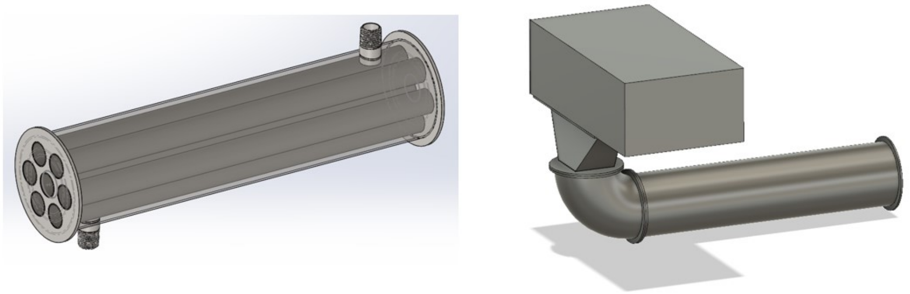


Figure 24: Counter flow shell and tube heat exchanger and primary and secondary heat exchangers

5.4.3 Drying chamber

The dryer module's function is to bring 3.5kg of 20% solid to 80% solid within an hour. The module consists of two main parts, a conveyance system and air heating. The conveyance system allows for the fecal sludge cake to be moved from input to output so the process can be continuous as opposed to batch. The air heating portion is to bring the heat from the working fluid to air which circulates in the dryer structure to aid in the evaporation of the water content. Fans attached to the radiator force the air over the sludge being dried on top of the plates.

The sizing of the conveyance system assumes the 20% solid has a density of 0.9g/cm^3, so 3.5kg being dried per hour with a thickness 0.5cm requires 7000cm^2.

$$Surface\ Area = \frac{density * mass}{desired\ thickness}$$

To account for errors, the design provides three shelves totaling 8300cm^2 of area for drying.

Figure 25: section view of drying chamber

5.4.4 Additional modules

Additional modules outside the scope of the prototype include a dewatering module which mechanically dewaters the input sludge from roughly 2% to 20%. Biomass or polymer is mixed with the sludge before being input to help flocculate and bring the solids together.

Another module is the power module which takes the waste heat from the combustion and generates electricity through a turbine or Stirling engine. For daily amount of 15,000L processed, approximately 400kWh of electricity would be produced. This electricity would be used for running the fecal sludge processor and selling back to the community.

The water separated from the sludge in the initial dewater stage and the drying stage is collected and processed so that it can be returned to the environment. This can be done with compression vapor distillation, chlorination, or UV treatment.

5.5 Conclusions

The designed lab scale fecal sludge processing system thermally dries waste to a fuel state, gasifies the dried waste to eliminate pathogens, then recaptures heat using heat exchangers. The lab scale I-OP processes 3.5kg of 20% solid per hour by thermally drying then gasifying. The thermal energy is recovered through the heat exchangers to run this continuous process. Future study would be required for the fabrication and testing of the I-OP.

6 System Complexity Analysis

6.1 Overview

System complexity analysis takes components, the interactions between components, and the structure of the interactions to quantify that entity. This type of analysis can give a method of comparing the technical difficulties (cost and effort) in design and operation between systems where the complexities are not as apparent.

The analysis of system complexity is discussed in *Structural complexity Quantification for Engineered Complex Systems* by Sinha and de Weck [36] and is applied to illustrate the differences between different fecal sludge treatment architectures. The analysis is done on a breakdown of the level 1 components identified [37] of fecal sludge treatment options, with a complexity of each component estimated by judgement. The relationships between each of the components are also considered, as is the structure of the relationships using a binary Design Structure Matrix (DSM). With graph theory, the energy of each DSM is calculated and then normalized for the number of components. The system complexity is a number that gives a sense of both the nature of the parts themselves and how they interact with each other.

The system complexity metric can be broken into three components: C_1, C_2, and C_3.

C_1 is the complexity of each part in the decomposed level, rated from 1-5 with 1 being the simplest and 5 being the most complex. C_2 is the score of the relational complexity between each of the components. This is calculated by representing the components of the same level in a Design Structure Matrix, then representing the interactions between components as a 1 and lack of interaction as a 0. C_3 is the energy of the DSM, so a hierarchal structure would have less energy than fully decentralized structure. The complexity is calculated by following equation:

$$C_{system} = \sum C_1 + \sum C_2\, C_3$$

6.2 Design Structure Matricies of different architectures

For each architecture, an engineering estimate is made on these level 2 decompositions of parts using information from the NIUA compendiums which also provide a detailed cost breakdown. Relationships between components are inferred from engineering experience and recorded. The results of this analysis is shown in Table 13.

Table 5: DSM for Pyrolysis

Part Complexity	**Pyrolysis**	Civil Engineering	Septage Receiving	Holding Tank	Pasteurization Unit	Dewatering Unit	Dryer	Treated water storage	Shipping Container	Pyrolizer	Control Unit	Ancillary Units
1	Civil Engineering	X	1									
1	Septage Receiving	1	X	1	1							
1	Holding Tank	1	1	X	1						1	
2	Pasteurization Unit		1	1	X	1			1			
3	Dewatering Unit				1	X	1		1		1	
4	Dryer					1	X		1		1	
1	Treated water storage						1	X	1			
1	Shipping Container				1	1	1	1	X	1	1	1
5	Pyrolizer								1	X	1	1
5	Control Unit			1			1	1	1	1	X	
3	Ancillary Units								1	1		X

DEWATS DSM

Table 6: DSM for DEWATS

Part Complexity		Feeding tank	Biogas digestor	Stabilization Reactor	Sludge Drying Bed	Collection Tank 1	Integrated Settler and ABR	Planted gravel Filter	Co-composting Unit
1	Feeding tank	X							
5	Biogas digestor	1	X	1					
3	Stabilization Reactor		1	X	1				
1	Sludge Drying Bed			1	X	1			1
1	Collection Tank 1				1	X	1		
3	Integrated Settler and ABR					1	X	1	1
3	Planted Gravel Filter						1	X	1
2	Co-composting Unit				1		1	1	X

InSanirator DSM

Table 7: DSM for InSanirator

Part Complexity		Civil	Septage Receiving	Holding Tank	Pasteurization Unit	Dewatering Unit	Dryer	Treated water storage	Shipping Container	Incinerator	Control Unit	Ancillary Units
1	Civil	X	1									
1	Septage Receiving	1	X	1	1							
1	Holding Tank	1	1	X	1						1	
2	Pasteurization Unit		1	1	X	1			1			
4	Dewatering Unit				1	X	1		1		1	
5	Dryer					1	X		1		1	
1	Treated water storage						1	X	1			
1	Shipping Container				1	1	1	1	X	1	1	1
5	Incinerator								1	X	1	1
5	Control Unit			1			1	1	1	1	X	
3	Ancillary Units								1	1		X

Upflow Anaerobic Sludge Blanket DSM

Table 8: DSM for UASB

Part Complexity		Holding Tank	UASB	Gas Collection	Pipes	Ancillary Units
1	Holding Tank	X				
5	UASB	1	X	1		1
4	Gas Collection		1	X	1	
1	Pipes			1	X	1
3	Ancillary Units		1		1	X

Co-Treatment DSM

Table 9: DSM for Co-treatment

Part Complexity		Inlet Channel	Settling-thickening tank	Unplanted drying Beds	Platform for sludge storage	Ancillary Units
1	Inlet Channel	X	1			
2	Settling-thickening tank	1	X	1		1
2	Unplanted drying Beds		1	X	1	
1	Platform for sludge storage			1	X	1
3	Ancillary Units		1		1	X

Planted Drying Bed DSM

Table 10: Plated Drying Bed DSM

Part Complexity		Planted Drying Beds	Horizontal Planted Gravel Filter	Polishing Pond	Greenhouse	Ancillary Units
1	Planted Drying Beds	X	1			
3	Horizontal Planted Gravel Filter	1	X	1		1
3	Polishing Pond		1	X	1	
2	Greenhouse			1	X	1
1	Ancillary Units		1		1	X

Drying Bed DSM

Table 11: Drying Bed DSM

Part Complexity		Drying Beds	Horizontal Gravel Filter	Polishing Pond	Ancillary Units
1	Drying Beds	X	1		
3	Horizontal Gravel Filter	1	X	1	
3	Polishing Pond		1	X	1
1	Ancillary Units			1	X

6.3 Results

Data taken from a Nation Institute of Urban Affairs Report on Fecal Sludge treatment options in 2018 [32] was compiled and then analyzed for system complexity. Detailed costs and breakdowns are from the Cost Analysis report of 2019 for different FSTP Options [37] and shown in Table 13.

Table 12: Complexity of FSTP Components

	DEWATS	Drying beds (w/co-composting)	Planted Drying Beds	Upflow Anaerobic Sludge Blanket	Co-treatment with STP	Pyrolysis	InSanirator
Components (C1)	19.0	8.0	10.0	14.0	9.0	27.0	29.0
Relationship (C2)	17.0	6.0	10.0	9.0	10.0	38.0	38.0
Structure (C3)	1.2	1.1	1.1	1.0	1.1	1.5	1.5
Total	39.4	14.7	21.2	22.6	20.2	84.7	86.7

Table 12 shows the results of the complexity analysis. As expected, the drying beds (co-composing and stand alone), UASB, and Co-treatment are the least complex fecal sludge treatment options. The drying beds utilize the sun to dewater and manual laborers or small machinery to distribute the sludge and remove it. The UASB is a passive process with minimal feedback. DEWATS is a process with several steps requiring human intervention, so its complexity is noticeably higher than the first four. Pyrolysis and InSanirator have the most complexity due to the machinery, mechanisms, and feedback loops which increases C2.

Table 13: Comparison of FSTP options

	Capacity (KL/D)	Area Requirement (m^2)	Capital Cost	Annual Operating Cost	Setup time	System Complexity
DEWATS	6	648	$95,622.00	$8,538.00	120	39.4
Sludge drying beds (w/co-composting)	12	27000	$ -	$19,210.00	75	14.7
Planted Drying Beds	12	720	$76,836.00	$14,184.00	90	21.2
Upflow Anaerobic Sludge Blanket	100	1200	$6,047,700.00	$38,400.00	240	22.6
Co-treatment with Sewage Treatment Plant	50	1000	$249,000.00	$24,900.00	53	20.2
Pyrolysis	15	929	$170,760.00	$21,345.00	105	84.7
InSanirator	15	60	$150,000.00	$9,600.00	7	86.7

The simplest systems which are drying beds have a low complexity due to the number of parts, while the DEWATS, Pyrolysis, and InSanirator have much higher levels due to the part count and interconnected nature of parts. Traditional fecal sludge treatment options utilized in the Indian market have lower system complexity

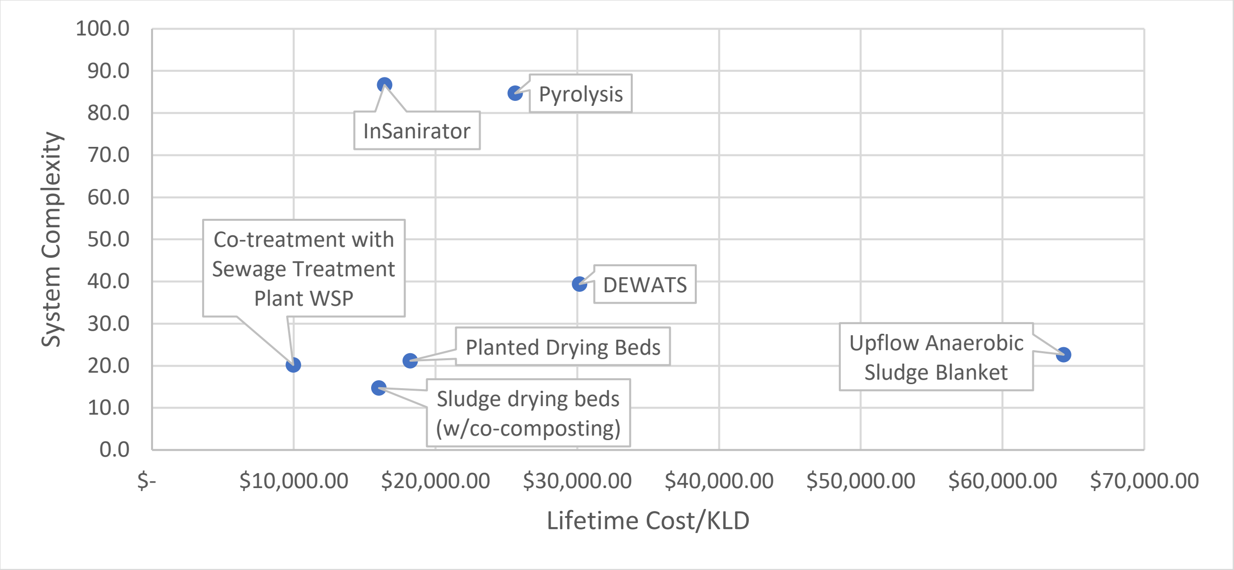


Figure 26: System Lifetime Cost versus Complexity

In Figure 26, the outputs of the complexity analysis have been plotted against lifetime cost per KLD. The lifetime cost per KLD was calculated using the equation below:

$$\frac{Cost_{Lifetime}}{KLD} = \frac{Capital\ Cost + 10 * Annual\ Operations\ Cost}{KLD}$$

The plot shows that lifetime costs per KLD does not necessarily rise with system complexity for a fielded product (Pyrolysis) and a product in design (Insanirator). While a lower system complexity may be beneficial for areas with less supporting infrastructure, the lifetime costs are not necessarily lower.

7 Economics of decentralized sludge treatment using Monte Carlo Simulations

7.1 Real Options Analysis Overview

The deployment of the I-OP is flexible in nature compared to a centralized waste water treatment plant supported by a sewer network because processing capability can easily be expanded or contracted by bringing in or moving away the containerized treatment plant. Additionally, the portability means the deployment can be spread over a geographical region to ease access for honey suckers who have fecal sludge to dispose of. Lastly, the resource recovery of water and electricity provides an option to monetize the output stream, possibly allowing the fecal sludge treatment plant to operate as a standalone business as opposed to a government owned entity or private public partnership.

7.2 Proposed implementation

Each fecal sludge treatment plant fits in a 20' shipping container and the land preparation requirements are a 15,000L tank for incoming material. According to interviews conducted in India and Bangladesh, the sludge per capita per day ranges from 0.1L-0.4L[23]. Factors contributing to the 0.1L are lining of the bottom of the tank and habits of users. Local laws in Indian cities require the septic tanks be sealed to prevent discharge without soak pits, but local preferences to minimize recurring vacuum truck costs steer tanks and pits to have open bottoms which allow the water to percolate into the ground [38]. The refugee camp treatment plant director saw 0.4L per capita per day due to the sealed pit liners since the water collection points are interspersed throughout the camp [23]. An unfortunate effect of having an on-demand transportation system is the 'leakage', or difference between generated sludge and properly collected and properly disposed of sludge. A city of 150,000 would need approximately three of these units to cover its average daily collection of sludge/septic tank output. The location of these should be optimized so that businesses who evacuate pit latrines would only have to drive a minimal distance to dispose of the material. The businesses evacuating the pit latrines have a strong preference to drive less than 10km away to dispose of the sludge in order to keep travel time and fuel consumption down.

The primary customer for this type of system would be a municipal government, with the beachhead market in India. Many of the semi urban areas are not supported by sewer systems and do not foresee the capital available to implement sewers for several decades. Currently, the fecal sludge is picked up by the honeysuckers, businesses with vacuum trucks which empty the latrines and tanks. The honeysuckers dispose of the sludge where possible, usually against environmental guidelines.

7.2.1 Strategy

In a traditional implementation strategy, a municipality would place tenders for companies to bid for, with the highest scoring bid winning. The bids are scored according to capital expenditure, operating expense, land use, technology, and other factors. A system similar to the one in this document could be more affordable in capital and operating cost and use less land than traditional methods. The contract would stipulate the payment terms of the capital expenditure, usually over the lifetime of the contract, the payment of the operating cost per month. In traditional fecal sludge and waste water systems, monetizable outputs are not produced.

A service focused strategy would follow models in leasing or the software world, where the implementation is done for a negligible fee and the capital and operation costs are paid for on a recurring basis as a subscription by the municipality.

A new potential model is the implementation at no cost and the only revenue from the selling of the resources recovered. This type of model would allow for the fastest market adoption, lowering the barrier of entry of capital and operating cost, only requiring land and operating permits. However, the revenue would need to offset the capital and operational expenses while providing an acceptable profit margin.

7.2.2 Revenue and marketing

The revenue of a system has several potential streams: capital, operating (if paid for by a municipality), and resources recovered. In the I-OP, the potentially monetizable outputs (and outcomes) would be water, electricity, nitrogen, phosphorus, and health data. Public health and environmental impacts are the desired outcome for the community, but more difficult to quantify.

The cost of the system is estimated to be $100,000 based on the bill of materials, labor in assembly, and shipping. The costing of the parts is estimated based on the size, material, and basic forming operations of each component. A potential price point is $150,000, which is 32% cheaper than competing systems, since municipal contracts are usually evaluated primarily on cost. The reduction in cost compared to other systems is done through design 1. in minimizing the footprint 2. choosing the simpler architecture, and 3. Providing provisions for a monetizable revenue stream. The operation revenue of a system is typically 20% of the sales cost per year, amounting to $2,500 per month while the cost of labor and consumables is approximately $6,40 per month. The electricity rate for locations in India are typically $0.10/kwh. Drinking quality water at $0.007/L and industrial quality water at $0.0005/L. Fertilizer is usually $0.45/kg. At the volumes of 15,000L per day and 408 kwh per day, the theoretical revenue for each year is $20,000. Net cash flow would be approximately $10,000, with costs of operation approximately $10,000.

7.2.3 Options for growth

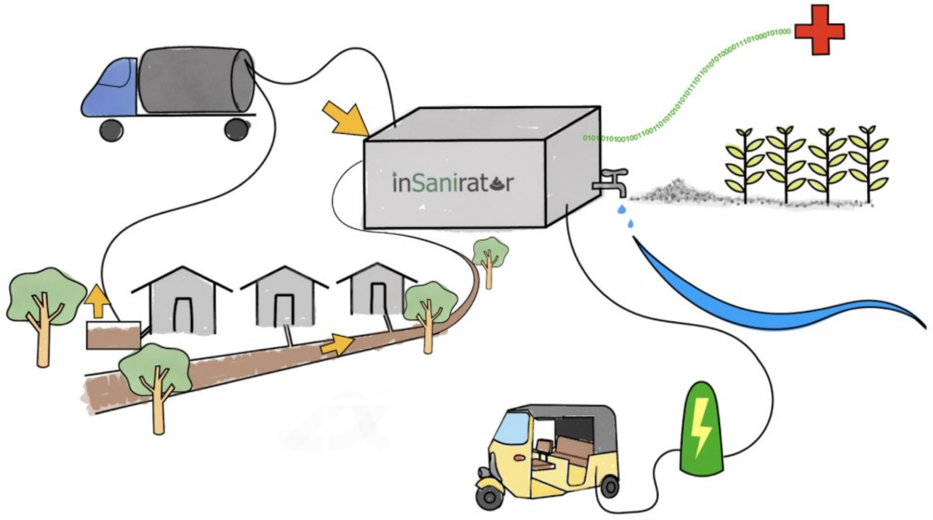


Figure 27: Artist's Rendering of System in Community

The system is decentralized and modular, meaning options for expansion and contraction exist compared to standard centralized systems. The main goal of a sanitation system is community health, and therefore safe processing of human waste. One possible metric to judge the implementation of the system is the ratio of waste treated versus total human waste created.

Methods to measure would be estimating the total waste created by multiplying the population by their estimated waste water per capita. Another method is measuring the amount of fecal sludge collected by the businesses over a period of time.

When the amount of treated waste approaches the limit of the system but is under the amount produced by the local population, a secondary treatment facility should be added. The location of the second facility can be collocated, but a better option is to spread locate the facility to ensure minimal transportation time for the businesses transporting waste.

The opposite case where a population starts to produce less waste is also possible. In the traditional waste water treatment plant, the operations still continue at the same cost, but less water is treated and less revenue generated. If a case occurs where the demand for waste processing drops enough to leave multiple plants under 50% capacity, one can be relocated to a different geography to save operating costs.

7.2.4 Anticipated outcomes

The goal for the implementation of this system is the affordable processing of human waste. A community which has this installed should have almost no fecal sludge or domestic sewage dumped into the environment. Local collectors who empty the community septic tanks and pit latrines would have a safer, closer place to dispose of the waste. In field trials of fecal sludge treatment plants, the waste collectors did appreciate having an official place to dispose of the waste.

7.3 Model Uncertainties

Sludge collected per day

The InSanirator processes the fecal sludge of a geographic area. The businessmen who evacuate the pit latrines and septic tanks want to minimize transportation time, so a radius of 10km is the practical maximum for service radius. Urbanization is increasing, which can bring more people into an area covered, or motivate them to leave. The number of people living in an area contributes heavily to the amount of human waste which needs to be processed.

A main factor in the usefulness and possible revenue stream is the average amount of sludge collected per day. The emptying and disposal of sludge/septage is dependent on 1. The storage tank and whether it drains to the ground water or is completely sealed and 2. The collection and delivery to the appropriate site as opposed to dumping it into the environment. The collection, transportation, and disposal methods are not perfect in containing human waste, adding an InSanirator should aid in the disposal method and make collection and transportation less risky.

The amount sludge collected per day is the number of people in the area multiplied by the average amount of sludge collected per person per day. The variable model accounts for a stochastic population growth rate each year while the amount of sludge per person per day is simulated to be a stochastic inverse of a normal distribution with a mean sludge generation of 0.15L per person per day.

Solid content of sludge

This uncertainty depends on the local water usage habits and the tank type. In areas with pour flush or flushing toilets, the waste water generation is higher than places with only pit latrines. Additionally, cultures using toilet paper will produce less waste water than cultures which use water to rinse.

Incentive cost

Changing the habits of the honeysuckers may require a monetary contribution for each load provided. In more mature markets where enforcement is strict, the honeysuckers could potentially pay a tipping fee for processing, but the launch of this system could require an incentive payment.

Mineral/metal recovery

In an ideal scenario, the InSanirator would have the ability to recover nitrogen, phosphorus, and metals like copper, silver, and gold, from the sludge, which is present in theoretically viable quantities. The model will simulate potential revenue for a system which can recover minerals and metal from the fecal sludge.

Sale price of water

A possible revenue stream for the water separated from the sludge and cleaned is to sell it for agricultural or industrial purposes. The best potential revenue stream is to purify it to a degree where it is suitable for drinking at $0.07/L, but the market feedback so far is overwhelmingly negative while industrial use water is approximately $0.0006/L [23].

Operational cost

Labor rates for regions vary, but in the best circumstance, and InSanirator only requires one worker to staff, while in other cases can have 5. The daily wages of the workers can range from $5 to $15.

Electrical Efficiency

Another potential revenue stream is the sale of electricity generated, which depends on the efficiency of our system. Within the model, a 15% thermal to electrical efficiency is used. For the dynamic model, Cost of system

The hardware, assembly, and shipping of the system drives initial costs while a learning rate over time drives cost down. Initial estimates of system cost is $60,000.

Electrical and Water efficiency of system

The InSanirator takes fecal sludge then processes it into water, electricity, and minerals. The recovery rate is a function of the system output and the inputs it receives.

Data Generation

In an effort to bring cities more data to make better decisions in serving the citizens, environmental data and analysis of the incoming fecal sludge can be provided to the municipality for a monthly fee.

Table 14: Sources of Uncertainties and distributions

Parameter	*Example Value*	*Mean Value*	*Standard Deviation or Min*	*Max*	*Distribution*
Population Served	31,807	50,000	15000		Normal
Sludge per person	0.07	0.15	0.07		Normal
Solid%	4.10%	2%	100.00	500.00	Uniform
Energy content of sludge (MJ/kg)	14.1	14	2.5		Normal
Sludge processing machine					
Cost of System	$64,852	$70,000	$60,000	120000	Normal
Machine Sales price	$122,655	$130,000	$10,000		Normal
Machine Capacity		15000			
Operational Cost	$750	800	150		Normal
Electricity Efficiency	13%	15	10	25	Uniform
Water Efficiency	57%	80	50	95	Uniform
Machine Maintenance contract per month % of sale price	$1,511	15%	5%		Normal
Mineral Recovery	$0	0.004	0.5		Normal
Data Generation	$457	$300	$100		Normal

7.4 Deterministic Results

The deterministic results are created using the cashflows by summing the revenues and costs for each year and a discount rate of 25%, computed over a span of 15 years. The discount rate of 25% is typical for ventures seeking funding. The base case in Table 15 shows the eNPV when the mean value of the row's variable is used. Example values are shown to demonstrate possible values used for the simulation.

Table 15: Effects of the uncertainties on eNPV

Uncertainties	Low NPV	High NPV	Base Case	Min	Base	Max
Mineral Recovery	$ 131,441	$ 2,960,918	$ 131,441	$ -	$ -	$ 10.00
Sales Price	$ (117,869)	$ 247,786	$ 131,441	$ -	$150,000.00	$ 220,000.00
Water Sales	$ 121,255	$ 324,977	$ 131,441	$ -	$ 0.50	$ 10.00
Sludge collected	$ 62,111	$ 313,888	$ 131,441	0.05	0.20	0.50
Population served	$ 71,458	$ 194,376	$ 131,441	25000	50000	75000
System Cost	$ 48,338	$ 164,682	$ 131,441	$ 50,000.00	$ 70,000.00	$ 120,000.00
Operational Cost	$ 38,239	$ 138,610	$ 131,441	$ 100.00	$ 200.00	$ 1,500.00
Solid %	$ 119,548	$ 167,121	$ 131,441	1%	2%	5%
Electricity Sales	$ 123,512	$ 147,299	$ 131,441	10.00	15.00	25.00
2-year load incentive	$ 126,348	$ 136,534	$ 131,441	$ -	$ 1.00	$ 2.00

The tornado chart in Figure 28 is created by plotting the maximum and minimum values of the static case NPV from Table 15 above. The maximum and minimum value from Mineral Recovery were $2,960,918 and $131,441 but were left off for scaling purposes.

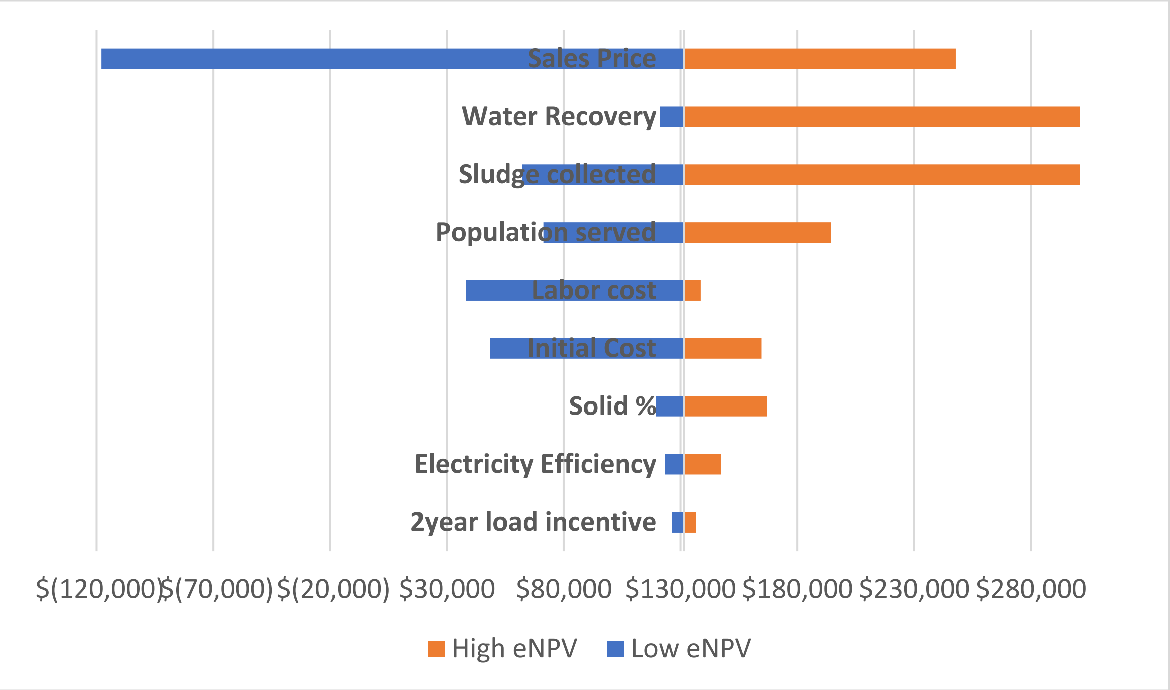


Figure 28: Tornado chart of uncertainties

The demand and finances are another representation over the course of time using the cashflows calculated.

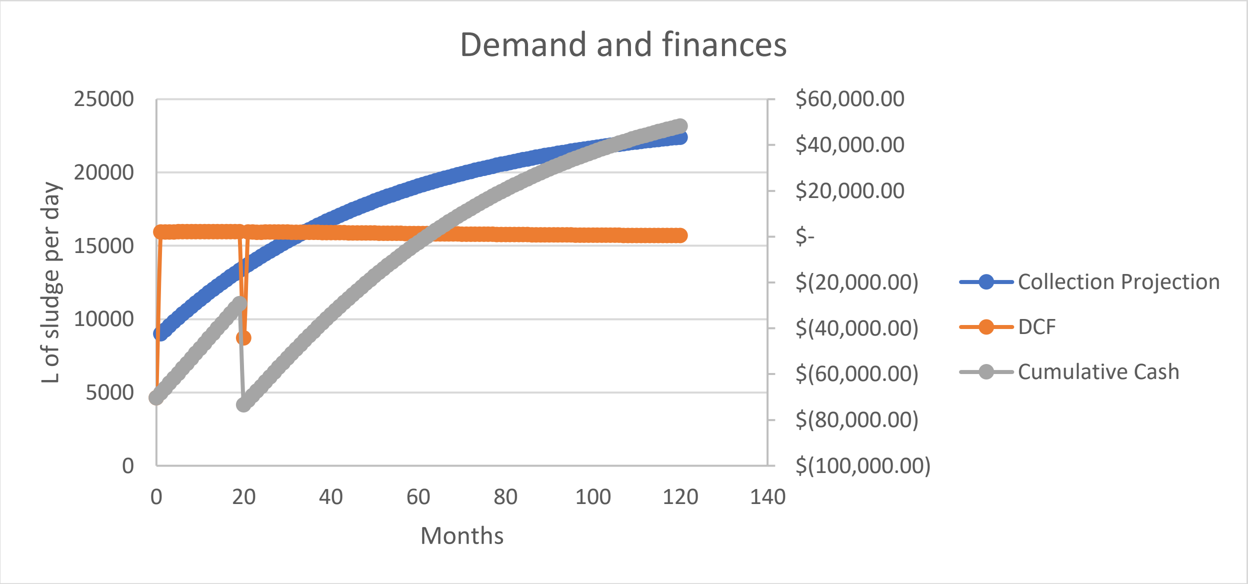


Figure 29: Revenue over time and L of sludge per day.

eNPV of ($70,221)

In this deterministic model, the downward spikes can be seen as capital cost being spent at the beginning and then during an expansion event, which occurs when the input to the fecal sludge treatment plant is at 90% of the capacity to ensure full coverage of sludge processing capability for the community. The tornado chart here reveals the promising nature of the mineral and metal recovery from the ash output. If it is possible to monetize this, sanitation technology can spread rapidly. Since this is a very difficult process, further analysis would need to be done on the feasibility for this function which is outside the scope of this document.

7.5 Responses to uncertainty

Population growth

In the case of rapid population growth, which can be expected in countries like India, expansion should occur adding additional InSanirators when the population or usage grows beyond a threshold to ensure adequate coverage of fecal sludge processing. The InSanirator is designed to be modular and scalable, so this option makes the most sense to explore.

Sludge collected per person

This is a factor which can be improved by incentivizing the sludge collectors to lower their prices, perform more collections, and dispose of the sludge at our facility. A sludge collector in India typically charges $20 to empty a 1,000-2,000L septic tank. That cost to the septic tank owners is high for their local wages. The disposal of the sludge incurs risks for the collectors given that dumping in the environment is illegal and punishable by jail time, beatings, and temporary confiscation of their vacuum truck. Incentivization could be accomplished by letting the collectors dispose the sludge for free while providing amenities like wash stations and food and beverages or even paying them for their raw material.

Solid content of sludge

To keep the system from needing to purchase electricity to run, the InSanirator could incorporate some biomass like sawdust to use as a solidifying agent and add additional fuel value to generate electricity and run the system. The sawdust sells for approximately $35/ton.

Mineral/metal recovery possible from the ash

The minimum viable product is focused on sanitation, so the mineral/metal recovery is a longer-term R&D effort. Without this revenue stream, the NPV is negative without capex from the government, so capital and operational expenses need to be covered in a more traditional method.

Sale price of water. Similar to mineral recovery, the MVP is focused on sanitation, with water sales being a longer-term effort. Without this revenue stream, the NPV is very negative, so capital and operational expenses need to be covered in a more traditional method.

7.6 Decision Rules

One likely decision rule would be to increase the number of units in the field by 1 when 90% of the region's capacity has been exceeded. This allows for the lead time to order, deliver, and setup the system without turning away the sludge collectors to ensure that sludge is disposed of properly in the area. This would be Case 2: Gov sale with expansion.

> *This is implemented with an IF statement: IF the sludge processed in the previous year is in excess of 90% of the capacity, then purchase and implement another unit.*

Another ideal decision rule is to rely on the monetization of the output streams and deploy this hardware for free. This is implemented by setting the sale price to zero and still implementing the if statement for expansion. Securing government contracts is contingent on the government 1. Wanting to buy the system 2. Winning the bid and 3. Securing payment, which occurs slowly according to interviews with competitors.

7.7 Results and discussions

With the Monte Carlo analysis incorporating the uncertainties affecting the viability of the deployment strategy, the following chart and table were produced.

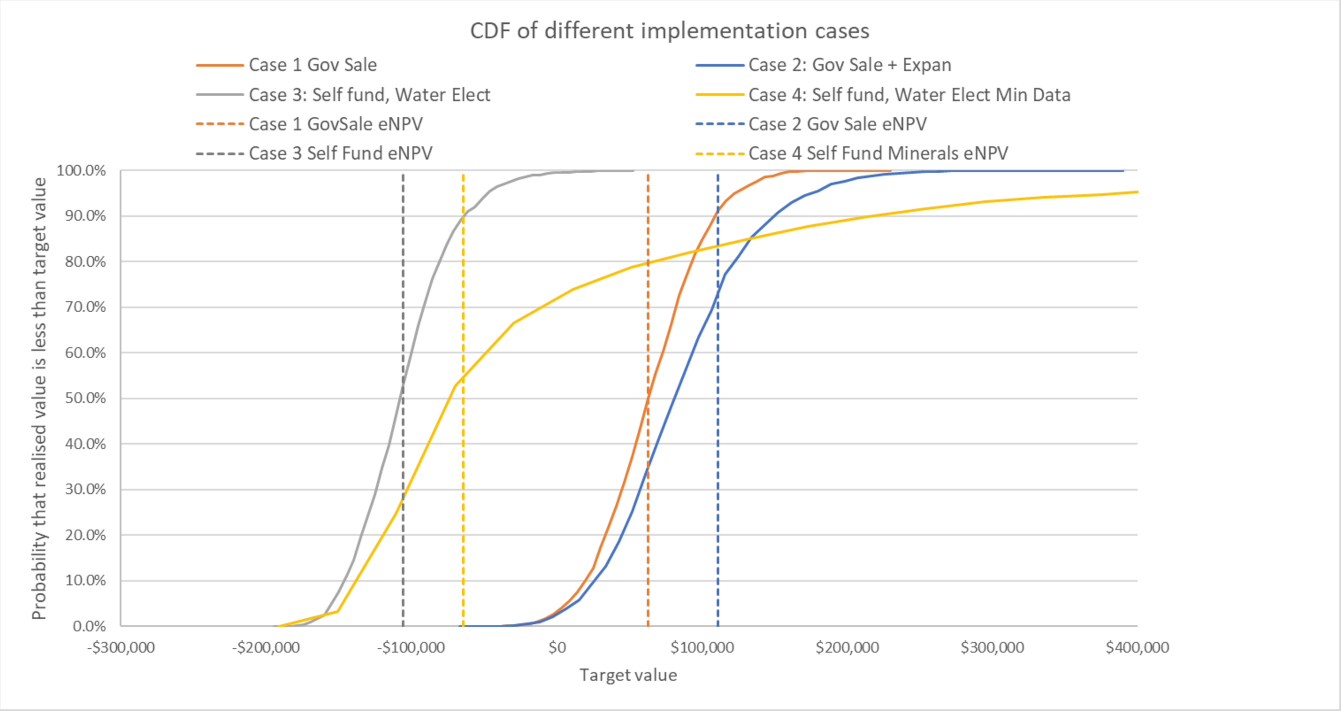


Figure 30: Viability of different implementation strategies

The target value shown in Figure 30 is the expected Net Present Value. A target value under $0 indicates the project is unable to make back its costs. A high target value suggests the machine and operations could operate as a standalone business.

In the table below, 4 scenarios are presented. The first scenario represents a typical Design, Build, Operate, and Transfer contract where a municipality purchases the hardware from a business for ~$150,000 and pays for the operation and maintenance. The responsibility of covering the expenses rests on the municipality and is resolved by charging tariffs on the sewage processing. The second scenario presents similar conditions, but with the ability to expand capacity by purchasing another unit to ensure complete fecal sludge processing for a growing population. The eNPV for both these cases can vary based on actual system cost compared to system sales price and the actual operational cost compared to contracted operational cost. In the majority of cases, the eNPV is positive, which is reflected in the steep distribution and positive values for the mean line.

Scenario three is a case where a company implements the system themselves and is responsible for the monetization though revenue generating streams such as the water at $0.50 per kiloliter and electricity at $0.10/kwh.

Scenario four is similar to scenario three, but with the additional revenue of selling data and minerals.

Table 16: Financial possibilities of strategies

	P_5	ENPV	St. Dev	P_{95}
Case 1 Gov sale	$3,000	$63,000	$35,000	$122,000
Case 2 Gov Sale with Expansion	$6,000	$111,000	$49,000	$171,000
Case 3 Self fund	-$160,000	-$105,000	$33,000	-$51,000
Case 4 Self fund + minerals and data	-$151,000	-$64,000	$189,000	$375,000

The traditional sales model is a capital upfront for the purchase and set up of the equipment, and the operation expenses for a fixed period of time. Theoretically in these traditional models, the return on hardware is positive, primarily because of the upfront money paid to cover the development, setup, and cost of hardware. However, in discussion with a company operating in India, they mentioned the government instead of paying up front, pays over a 10-year period.

However, the ideal case in rapidly scaling sanitation technology is a situation where there is minimal capital cost, which is a high barrier to scaling. The scaling in this case is the implementation in various municipalities in India. Over 7,000 semi urban villages exist which could be viable candidates for deployment. In this case, the sale of water, electricity, and data potentially can make up for the upfront hardware. Using the variables presented however, it is difficult to make a case for monetizing water, electricity, and data, even with maintenance costs covered by the government.

During preliminary analysis, appealing maximum revenue estimates showed immense potentials for implementing this strategy in a profitable and rapidly deployable manner. Unfortunately, the preliminary results from this analysis reveals the headwinds of monetizing these small transactions.

Table 17 below shows the excel model with revenues and expenses listed for scenario 3.

Table 17: Sample of Excel model with Revenues and Costs (first 3 years shown)

Units deployed this year	1	0	0
Sludge Process Capability per year	5475000	5475000	5475000
Solids Capability	195458	195458	195458
Excess Sludge capacity		2270076	1898052
Excess Solids Capacity		81042	67760
Capex Revenue	$ -	$ -	$ -
Maintenance Revenue		$ -	$ -
Water Revenue		$ 1,375.28	$ 1,534.92
Electricity Revenue		$ 9,177.11	$ 10,242.37
Capital Cost	$ 118,454.00	$ -	$ -
Operations cost	$ 6,557.50	$ 6,557.50	$ (6,557.50)
Incentive Cost		$ (1,281.97)	$ (1,430.78)
Total Revenue	$ -	$ 10,552.38	$ 11,777.29
Total Expenses	$ (125,011.50)	$ (7,839.47)	$ (7,988.28)
Cashflow	$ (125,011.50)	$ 2,712.91	$ 3,789.01
Discounted Cashflow	$ (125,011.50)	$ 2,170.33	$ 2,424.97
NPV	$ (108,657.67)		

The water rate used for the calculations above are $0.50 per kiloliter and $0.10 per kWh. The revenue varies based on the amount of sludge processed, which varies with population. The largest change is the potential monetization of minerals and metals found in the sludge. This is a long-term R&D effort, but a successful module which could do this can change the implementation of sanitation. An interesting point of consideration is the large uncertainty in mineral prices, due to the immature process of metal collection from fecal sludge ash in a small-scale system. The extremely large standard deviation and maximum value for Case 4 shows an appealing case, but the lower eNPVs show the difficulty of monetizing outputs to deploy sanitation technology for free.

7.8 Conclusion

In operating a system like the I-OP, the most financially viable scenario is selling to governments in Design, Build, Operate, and Transfer contracts. The revenue is consistent and can support the capital cost to build the hardware. Relying solely on monetizing processed outputs from fecal sludge is extremely difficult; the only scenarios showing a positive eNPV required recovering metals and minerals from ash, which is not a mature process.

A government purchasing a system like this through a DBOT contract should account for variations in population, especially in areas of growth. Expansion options should be considered to ensure all fecal sludge generated by the community can be processed. The waste collectors will need to change their behavior to properly dispose of the fecal sludge, so enforcement of policy or incentivizing payments need to be considered.

8 Conclusions

In this thesis, the sanitation context was discussed. An innovative system to process fecal sludge was proposed, and a concept prototype was fabricated. The building of the prototype required more time and effort than expected, meaning testing was unable to be completed.

A trade space analysis was completed which shows the cost effectiveness of unsewered, decentralized systems and the potential for affordable yet safe sanitation solutions. Plotting the community health cost versus dollar cost per capita corroborates the notion that while manual scavenging and open sewers are the most affordable, the health costs are the highest. In order to maximize community health at the lowest dollar price, a distributed fecal sludge treatment system, combined with mechanized transport shows the most promise.

The system complexity analysis indicated that solutions with more machinery and parts were indeed more complex, but the operating expenses did not necessarily correlate with the system complexity score.

A Monte Carlo analysis with real options indicated the traditional government contract model to have the highest expected Net Present Value, even though the potential of resource recovery and reuse is extremely high. A business starting in this market should seek to start with the traditional contract model for best financial viability.

The limitations of this work are the first order estimates for the tradespace, systems complexity, and economic analysis. More detailed analysis should be taken for those aspects. Construction and testing of the I-OP to assess the efficiency is a concrete step which can be further taken.

9 References

[1] P. Bracken, C. Werner, and E. Kvarnström, “Making sustainable choices-the development and use of sustainability oriented criteria in sanitary decision making.”

[2] “Pathogens in Human Excreta: SulabhENVIS Centre.” [Online]. Available: http://www.sulabhenvis.nic.in/Database/sanitation_humanexcreta_2131.aspx. [Accessed: 23-Jul-2019].

[3] E. Chaggu, J. Van Buuren, W. Sanders, and G. Lettinga, “PROFILE Excreta Disposal in Dar-es-Salaam,” 2002.

[4] B. Genser *et al.*, “Impact of a city-wide sanitation intervention in a large urban centre on social, environmental and behavioural determinants of childhood diarrhoea: analysis of two cohort studies,” *Int. J. Epidemiol.*, vol. 37, pp. 831–840, 2008.

[5] A. Y. Katukiza, M. Ronteltap, A. Oleja, C. B. Niwagaba, F. Kansiime, and P. N. L. Lens, “Selection of sustainable sanitation technologies for urban slums-A case of Bwaise III in Kampala, Uganda,” 2010.

[6] D. Mara, J. Lane, B. Scott, and D. Trouba, “Sanitation and Health Introduction and Definitions.”

[7] R. W. Crites and G. Tchobanoglous, *Small and Decentralized Wastewater Management Systems*. WCB/McGraw-Hill, 1998.

[8] G. Hutton and L. Haller, “Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the Global Level,” 1994.

[9] S. Cairns-Smith, H. Hill, and E. Nazarenko, “Urban sanitation: Why a portfolio of solutions is needed,” 2014.

[10] K. C. Rao, E. Kvarnström, L. Di Mario, and P. Drechsel, “RESOURCE RECOVERY & REUSE SERIES 6 6 Business Models for Fecal Sludge Management.”

[11] D. Koné, “Making urban excreta and wastewater management contribute to cities’ economic development: A paradigm shift,” *Water Policy*, vol. 12, no. 4, pp. 602–610, 2010.

[12] G. Hutton and M. Varughese, “The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water, Sanitation, and Hygiene,” 2016.

[13] P. Drechsel, C. A. Scott, L. Raschid-Sally, M. Redwood, and A. Bahri, *Wastewater Irrigation and Health Assessing and Mitigating Risk in Low-Income Countries Wastewater Irrigation and Health Earthscan strives to minimize its impact on the environment Water / Agriculture and Food / Development*. .

[14] M. Haraguchi, A. Siddiqi, and V. Narayanamurti, “Stochastic cost-benefit analysis of urban waste-to-energy systems,” 2019.

[15] “What is a Circular Economy? | Ellen MacArthur Foundation.” [Online]. Available: https://www.ellenmacarthurfoundation.org/circular-economy/concept. [Accessed: 19-Aug-2019].

[16] S. Trémolet, “Identifying the Potential for Results-Based Financing for Sanitation Scaling Up Rural Sanitation,” 2011.

[17] L. Strande, M. Ronteltap, and D. Brdjanovic, “Systems Approach for Implementation and Operation Faecal Sludge Management.”

[18] A. M. Muspratt *et al.*, “Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal,” 2014.

[19] C. Paterson, D. Mara, and T. Curtis, “Pro-poor sanitation technologies,” *Geoforum*, vol. 38, no. 5, pp. 901–907, 2007.

[20] A. Bakalian, A. Wright, R. Otis, J. De, and A. Netto, “Simplified Sewerage: Design Guidelines,” 1994.

[21] A. Tsang, “Interview with Kutupalong worker,” *N/A*, 2018.

[22] N. Chamma, “Rethinking Refugee Camp Design : From ’ Temporary ’ Camps To Sustainable,” no. November 2016, 2017.

[23] A. Tsang, “Takeaways from India/Bangladesh Trip,” *N/A*, 2018.

[24] L. Ulrich, P. Salian, C. Saul, S. Justrich, and C. Luthi, “Assessing the Costs of on-site sanitation facilities,” no. March, p. 27, 2016.

[25] Diana Yousef, “Our Solution — change:WATER Labs.” [Online]. Available: http://www.change-water.com/solution. [Accessed: 21-Jul-2019].

[26] “Wastewater Technology Fact Sheet Anaerobic Lagoons.”

[27] S. Newey, “Largest-ever sewage treatment plant opens in Bangladesh refugee camp Cox’s Bazar,” 2019. [Online]. Available: https://www.telegraph.co.uk/news/0/largest-ever-sewage-treatment-plant-opens-bangladesh-refugee/. [Accessed: 25-May-2019].

[28] A. Tsang and D. Peterson, “Interview with Greece Refugee Camp worker,” 2018.

[29] P. Bracken, C. Werner, and E. Kvarnström, “Making sustainable choices-the development and use of sustainability oriented criteria in sanitary decision making.”

[30] “The Fossa alterna-the double pit compost toilet.”

[31] P.-H. Dodane, M. Mbéguéré, M. Mbéguérémbéguéré, O. Sow, and L. Strande, “Capital and Operating Costs of Full-Scale Fecal Sludge Management and Wastewater Treatment Systems in Dakar, Senegal,” *Environ. Sci. Technol*, vol. 46, pp. 3705–3711, 2012.

[32] S. Capacity and B. Platform, “Faecal Sludge Treatment Technologies in India - Compendium,” 2018.

[33] A. Edathoot, “Anaerobic Baffle Reactor | SSWM - Find tools for sustainable sanitation and water management!” [Online]. Available: https://sswm.info/step-nawatech/module-1-nawatech-basics/appropriate-technologies-0/anaerobic-baffle-reactor. [Accessed: 25-May-2019].

[34] H. E. Muga and J. R. Mihelcic, “Sustainability of wastewater treatment technologies,” *J. Environ. Manage.*, vol. 88, no. 3, pp. 437–447, Aug. 2008.

[35] V. Chandrashekhar, “Dying Waters: India Struggles to Clean Up its Polluted Urban Rivers,” 2018.

[36] K. Sinha and O. L. de Weck, “Structural Complexity Quantification for Engineered Complex Systems and Implications on System Architecture and Design,” p. V03AT03A044, 2014.

[37] L. C. Costing, “Cost Analysis of Faecal Sludge Treatment Plants in India.”

[38] “Scoping Exercise to Support Sustainable Urban Sanitation in Tamil Nadu PRIMARY STUDY REPORT Volume I,” 2016.