World Vision Challenge: Affordable Rural Single-Family Sanitation

Challenge ID: 9934301 Deadline: 12 Jan 2021 23:59 EST

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Abstract of the solution

The present proposal encompasses a set of modules allowing 20 combinations in order to meet the local needs and cultural acceptance of the widest range of potential users. The said modules are:

1. a superstructure that complies with the European standard **EN 16194** ([i]), i.e. exceeds the Challenge's requirements,
2. some optional features, not mandatory by the said standard or by the Challenge, but potentially desirable in many contexts (e.g. a kit to make the superstructure resistant up to Class I hurricanes, several solutions of low-cost hands washing stations, etc.),
3. two variants of interface: with squatting podium and with seat, in order to meet the cultural preferences of one type or the other;
4. one low-cost container for collecting and maturing the urine,
5. two concepts of containment system for the faeces and absorbent litter: passive (high volume, long maturation time, one day every 6 months for maintenance, only use as soil conditioner) and active (small volume, a few minutes a week for processing the waste, full disinfection by high temperature, energy recovery and carbon sink). The "passive" concept is presented in 3 variants and the "active" concepts is represented by two variants.

All the possible combinations arising from the said modules have the following features in common:

1. The design is based on the urine-diverting-dry-toilet (UDDT) concept. The reason for this choice is that most of the low-income population lacking modern sanitary infrastructure lives in tropical or subtropical rural areas, where sourcing water for the family is a hard burden on women and girls. Furthermore, the said concept allows recovering the urine (80% of the nutrients in human excreta) and the carbon in the faeces and absorbent litter, for their safe use in agriculture.
2. The design is so simple that anybody can build it with hand tools.
3. The material of choice for most of the elements is a compound of vegetal fibres mineralized with a very small quantity of Portland cement. The said materials are ubiquitous, and the price of Portland cement is more or less uniform throughout the world, allowing an easy implementation everywhere and the comparability of the results. Other materials are required in small quantities: screws, metal brackets, wire, etc., all available in any hardware shop.

The design (measures and operational features) is fully compliant with the European norm **EN 16194**, meaning that it is applicable only to users that do not need a wheelchair to move**.** Restrooms for people on a wheelchair must comply with a different norm, which requires 8 times more material than a restroom for people with no (or with light) motorial disability hence, a solution for severely disabled people will not meet the 45 US$ maximum cost required by the challenge. The present solution considers only aids for users with "reduced motorial ability" (e.g., elderly people, pregnant women, victims of amputation or poliomyelitis, etc.). Altogether, people with normal and reduced motorial ability represent more than 99% of the population.

If ensuring only the **minimum compliancy** with the Challenge's prescriptions, the cost ranges from **33.28 US$ (squatting podium) to 35.17 US$ (seat on a higher podium).** Adding some additional functions not requested by the Challenge (resistant to Class I hurricanes, integrated hands washing station, replacing the containment volume with a gasification stove to recover the litter as fuel for saving firewood, a 70 l water tank for rain harvesting integrated on the roof) **the cost is still within the Challenge's limit: 43.85 US$**.

Introduction and Background

Complex problems like providing safe sanitary services at costs affordable for low-income populations have no single solution. The optimum solution for each case will depend on the context and design constraints like:

a) the local climate,

b) the easy access to water,

c) the available construction materials and their local costs,

d) religious beliefs, traditional defecating posture or other cultural factors,

e) the average age of the population and,

f) the percentage of people having some degree of disability that may require special design features.

The Solver followed the design criteria for WCs placed in open areas (construction yards, fairs, concerts, etc.) contained in the European norm *EN 16194 Mobile non-sewer-connected toilet cabins*, applicable to users that do not require a wheelchair to move. The said norm includes all the requirements of the Challenge and a few more. For the purpose of this Challenge, the desired restroom for a rural family will not be "mobile" in the sense of the cited EN standard, although it may be moved and repositioned a few meters away or, in the worst case, dismantled and rebuilt somewhere else. On the other hand, most rural areas in Developing Countries are subject to periodical monsoons or cyclones, so ensuring the stability and durability of the construction in high winds poses further design constrains, not foreseen in the EN16194 because there are no cyclones in Europe, and apparently not considered by the Seeker. As an example, figures 1 and 2 show two Italian commercial products that comply with the said norm. The Solver carried out the stability verifications of his design based on standard engineering formulas for wind loads, while the aerodynamic data for a square flat plate (roof) were taken from the literature.

Photo 1: regular quality prefabricated WC to be used in construction yards (1 restroom every 10 workers), outdoors concerts, fairs and similar events, compliant with EN 16194. The superstructure is made of insulating panels, in order to provide thermal comfort also under European winter conditions. Price in Italy 1300 €, source https://macchedil.com/store/bagni-chimici-wc/bagno-coibentato-scarico/. Some top-quality products can cost up to 2500 €.

Photo 2: A cheaper toilet to be employed with limited public (for instance, to be installed in a home's garden, or a farm or a small construction yard). Price 433 €. Source http://web.tiscali.it/waldem/wcchimici/index.htm

The design assumptions that led to the present solution are the following:

a) The Solver **arbitrarily** supposed that the solution will be built in Ethiopia. For the purpose of this challenge, Ethiopia can be considered as an archetype of the Sub-Saharan Countries because 79% of its population is classified as "rural" according to the World Bank ([ii]). Within the large variety of bioclimatic zones in Ethiopia, the savanna environment (Adama region, photo 3) is representative of most rural areas across the world, not only in Africa, so the Solver assumed that a solution suitable for this environment can be applied successfully in a wide range of places, with small variability of the construction cost. The calculations herein have the value of example, the Solver's intention is to provide as much detail as possible in order to allow the Seeker to easily adapt the solution to different environments (e.g. rainy subtropical African or Asian countries) or to special cases, and re-calculate the cost by just entering the prices of the local market.

Photo 3: Savanna environment assumed as model, Adama, Ethiopia. Source: https://allytravel.wordpress.com/day-tours/adamanazret-day-tour/

b) The standard solution proposed here (people that do need a wheelchair to move) should cost less than 45 US$, as defined by the challenge. The Solver based his estimations on the unitary construction costs from the following Ethiopian web portals: https://constructioninethiopia.com/construction-materials-in-ethiopia/, https://www.ethiopianconstruction.com/ethiopian-construction-material-cost, https://akerabi.com.et/construction-materials/, and https://con.2merkato.com/.

c) The exchange rate assumed for the cost calculations is 1 US$ = 37 ETB, retrieved from https://www.exchangerates.org.uk/Dollars-to-Ethiopian-Birr-currency-conversion-page.html on 18/10/2020.

d) The use of free materials or components, either naturally available or recycled, has the priority on the purchase of commercial items. Nevertheless, the Solver assumed that the users of this solution have just basic construction skills, so the design is minimalist and functional: cost and ease of construction have the priority on aesthetical factors.

e) The design should be as carbon-neutral as possible and minimize the use of timber, not to contribute to forest depletion. This is not an explicit requirement of the Challenge, but the Solver is ethically concerned about the said problems and considered them when checking alternatives.

f) The labour cost is null because the solution is easy enough to allow the self-construction with simple hand tools and minimum skills.

g) The demographic data are those of the Oromia region since it has the biggest rural population in Ethiopia ([iii]).

h) Within the Oromia region, the climate data are those of the savanna environment of Adama ([iv]), because a large percentage of the world's rural population lives in savanna-like areas similar to this.

i) A solution specially designed for users moving on a wheelchair is excluded for the reasons explained in the abstract and should be developed separately. The rationale for this decision is justified by a South African study, which was the only accessible for free that the Solver could found with an internet search ([v]). The percentage of disabled people in Africa is roughly 10 %, but the percentage of people with "severe disability", i.e. those who may need assistance for defecating because of motorial impairment, is less or equal to 1%. Another bibliographic source from the University of Leyden (https://www.ascleiden.nl/content/webdossiers/disability-africa#Physical%20disability) seems to confirm the said assumption (most papers focused on blindness or dumb-deafness). Unfortunately, the few statistical data on motorial disability in the library of the cited university are not accessible to the public. From the available abstracts, it is possible to infer that people with a degree of motorial disability requiring a wheelchair do not live in rural areas, but are usually sent by their families to urban areas. So, the Solver considered that it is not logic developing a solution allowing the usability for severely disabled people, exceeding then the 45 US$ limit set by the Challenge, if the probability of finding users with such requirements in rural areas is almost null.

j) The area lacks current water, electricity and motor-driven pumps or a windmill. Sourcing water in Developing Countries, especially in dry Sub-Saharan Africa, usually burdens girls and women, with 61 million people lacking access to water only in Ethiopia (https://www.globalcitizen.org/en/content/water-org-ethiopia-water-crisis-women/). A solution that requires water for flushing and/or treating the excreta is ethically unacceptable under the said conditions, hence the Solver decided to discard chemical toilets, biotechnological toilets ([vi]), septic tanks and digesters. The only alternative is then the "dry" type of toilet. Furthermore, the Challenge explicitly states that the users will be a "rural single family". It must be observed that many of the examples shown in the literature provided with the Challenge's definition refer to experiences conducted in poor suburban areas, where plastic film bags and water are easier to source than in a rural context, and for that reason most of the examples correspond to flush toilets and single-use bags. On the other hand, a rural environment can provide lots of natural absorbent material for free (cereal husks, dry leaves, loose soil, sand…) so this is another argument in favour of adopting a dry toilet design.

k) Digging is not always feasible in rocky places or arid soils, and is a hard work in tropical weather conditions, so the containment system should require a pit with the smallest volume possible. This assumption is in conflict with the Challenge's requirement of "at least 2 m^3 of containment volume", leading automatically to the next consideration.

l) Since the toilet must be of the dry type by the assumption k), this means that the excreta must be either composted or thermally treated. The Solver excluded composting for the following reasons:

   i. it is a process that requires a critical mass of organic matter having "a structure" in order to allow air to circulate;

   ii. the geometry of the composting pile must be such that it is possible to reach a temperature between 50°C and 70°C, otherwise the process is ineffective;

   iii. industrial composting of urban garbage requires adding "structuring material" (rests from gardening, chopped cardboard, chipped bark or wood) in order to achieve the necessary "structure" to allow the air circulation and then air is injected in composting chambers at a controlled rate. Both techniques are inapplicable at domestic scale, and probably this is the reason why the literature provided with the Challenge ([vii]) refers that “composting chambers are not that easy to operate”. The composting chamber described in the reference book requires a fan to ensure adequate oxygenation, which is a reasonable option for the Country where it was developed (Australia) but it is not a viable option in a rural area lacking electricity as assumed in k).

iv. The design of the composting chamber shown in the reference (corresponding to the Clivus Multrum™ commercial model, https://en.wikipedia.org/wiki/Clivus_Multrum) is, in the opinion of the Solver, suitable for a household in and industrialized Country and furthermore in temperate-cold climate. The system depicted in the reference manual looks like a linear scale-down of an industrial composting facility. Furthermore, a fan will of course provide fresh air for the oxidation, but too much fresh air will lower the temperature, hindering the very essence of composting, i.e. reaching 60-70°C for at least 5 days. If the quantity of wet organic matter is small, it is then impossible to reach the “critical mass” required for a “standard” composting process at 60 – 70°C.

v. The oxidation of organic matter during the composting process has another drawback affecting the compost’s quality as a fertilizer: C is lost as CO_2. The use of composting toilets in rural areas of Australia was the subject of a postdoc thesis available online ([viii]). The same provides evidence of the operational problems of two models tested in the field: the Clivus Multrum™ and the RotaLoo™ (http://www.rotaloo.com.au/). The study shows some examples of self-made composting chambers that seemed to work, but the cost is prohibitive, and also some reference to vermicomposting (Dowmus ™, https://cgi.tu-harburg.de/~awwweb/wbt/emwater/lessons/lesson_b1/lm_pg_1206.html, the company bankrupted http://rammedearth.davis.net.au/toilet.htm so probably the system was not as good as they claimed). Vermicomposting works well for kitchen waste but earthworms have little tolerance to the ammonia contained in urine and faeces.

All the said evidences led the Solver to exclude composting as a viable alternative for the scope of this challenge. The Solver proposes an improved version of the urine diverting dehydrating toilet (UDDT). The urine will be then collected separately and employed as a liquid fertilizer because it is basically sterile and contains 80% of all the nutrients in human excreta (ref. [xiv]). An UDDT with sub-soil application of the urine (and eventually grey water from washing too) ensures no odorous emissions and the full recycling of the nutrients and water for food production, which is imperative in the target socio-economical environment assumed for this Solution. The faeces are a potential vector of pathogens, so the mixture of faeces and litter material will be “actively” treated or “passively” stored for maturation, as explained in the corresponding section, in order to make it safe to use as soil conditioner. The consequence of these consideration is that the “containment system” required by the Challenge consists actually on two elements: a tank for urine collection and a box or any other container for receiving and storing the faeces and absorbent litter.

m) The Challenge does not state how many individuals compose the “single family”. The Solver assumed 6 individuals based on statistical information of the UN for Africa ([ix]). The quantity of excreta was then assumed as an average of 0.4 kg/day faeces (nearly 50% moisture) and 1.01 l/day urine (252 ml 4 times/day) based on the information published by the WHO guidelines on sanitation ([x]). The average concentration of N in the urine is assumed to be 5 g/l (same WHO guidelines). It is also assumed that only crops with high N demand will be irrigated with the urine and eventually water from the washing. The N uptake ranges from a minimum of 10 g/m^2 (tomatoes, lettuce, sweet peppers, cucumbers, watermelons), through 26 g/m^2 (sweet corn) to a maximum of 38 g/m^2 (onions and potatoes) (ref. [xi]). An average dose of 25 g/m^2 should be adequate for most of them, especially if planted in rotation. Hence, the minimum area for spreading the liquid collected from the toilet will be 442 m^2, i.e. a square of 21 x 21 m. Spreading the urine overall the said area as uniformly as possible throughout the year will ensure that little or no nutrients will leach to the underground water because the plants will readily absorb them. The Solver will not enter into details on how the urine and water collected from the toilet will be applied, since the subject is out of the scope of the Challenge and is already explained in detail in ref. [xii]. According to the latter, two weeks of seasoning at room temperature is enough to make the urine safe for its direct use as a fertilizer, and some crops can be safely fertilized with fresh urine too. Hence, for the purpose of this Challenge the Solver assumes that the urine storage volume must be at least 14 days x 6 people x 1.01 l/day = 85 litres.

Detailed Description of the solution

1) Superstructure

The minimum inner size according to the **EN 16194** is 1 m x 1 m x 2 m. The Solver checked the construction cost of a cabinet with the said measures in Ethiopia, assuming the following possibilities:

a. Galvanized steel plate on steel profiles, brick floor

b. 100% plywood;

c. 100% timber (planks 20 cm x 400 cm x 2 cm)

d. a tent of tarpaulin on a timber frame with brick floor;

e. 100% concrete blocks of 10 cm thickness (the cheapest ones);

f. a timber structure with walls of straw bales, thatched roof and brick floor;

g. walls of clay bricks reinforced with a mat of reeds or straw (traditional adobe construction of Latin America), thatched roof and brick floor;

h. woven mats or bundles of locally available vegetal fibres (reeds, straw, palm leaves, bamboo), secured with galvanized wire on a timber frame (a technique called “quincho” in Argentina and Uruguay, which is mainly applied for thatching but can be also employed for vertical walls), with brick floor and timber door;

i. a timber frame covered with recycled jute sacks (e.g. those employed for potatoes, coffee and cereals) and several other variants described in a guideline of the World Health Organization (WHO, https://www.who.int/docstore/water_sanitation_health/onsitesan/ch04.htm).

Options a) to e) resulted in overall construction costs much higher than 45 US$ under the assumed conditions (calculations available if the Seeker wants to check them). Option f) requires a kind of press made of timber in order to form acceptable straw bales, which would cost 30 – 40 US$. Options g) to i) may cost less than 45 US$ but together with f) present several weak points:

i. Irregular surfaces which are difficult to clean;

ii. insects, snakes and rodents can nest in the straw or reed bundles (e.g. the Solver has direct knowledge of the problems associated to the “*quincho*” construction, widely diffused in Northern rural Argentina, Paraguay and Southern Brazil, where it propagates the Chagas disease, transmitted by *Triatoma infestans* -an insect that nests in the reed thatching and vectors the protozoan parasite *Trypanosoma cruzi*);

iii. they are not "universally applicable", in the sense that sun-dried clay may be a suitable material for the assumed Ethiopian savanna environment, but it is not in rainy places like Virunga (Congo) or SE Asia. Conversely, mats of woven bamboo are common and cheap in humid tropical countries like Vietnam or India, but bamboo is unavailable in dry savannas. Palms having leaves long enough to allow weaving a mat are not ubiquitous, and many palm species have short leaves. Jute sacks may not be available everywhere.

The Solver proposes that the three walls, door, floor and roof are made of panels produced onsite with locally available vegetal fibres (sorghum panicles, bamboo strips, coir, chipped palm leaves, chopped straw, reeds), agglomerated with cement. The panels will be joined with screws or long nails or steel wire. Only basic hand tools are necessary. The panels will be 100 x 200 x 2 cm. Such kind of panels is available in Italy with the brand Eraclit since 1925 ([xiii]). The material looks like photo 4. In the original Italian product, the binder is magnesite, pressed together with the fibres at hight temperature. A product cheaper than the original Eraclit, manufactured by Celenit ([xiv]) is made with 2/3 wood fibres and 1/3 Portland cement. It is relatively easy to handcraft a product similar to Celenit, though at least 20 days will be required for curing the cement and reaching a good strength for panel handling, nailing, screwing, etc. The resulting panels do not rot, even if placed directly in contact with the moist ground, are incombustible, and have good thermal and mechanical properties. They can be cut with a fine-teethed saw, nailed, drilled, screwed, sanded, plastered and painted, like plywood or plasterboard panels.

CAVEAT

When attempting to make at home this kind of panels, please use only good quality Portland cement, clean sweet water and <u>dry vegetal fibre</u> that must be 50 – 100 mm long and soaked in clean water at least overnight just before preparing the mixture. <u>Forget about adding rice husk, sawdust, bark, sand, quick lime, chalk, gravel, clay or any other similar loads, since the resulting panels will be too weak</u>. Do not use fresh (green) vegetal fibres, because the sugars and starch they contain will react with the cement, weakening it. Suitable fibres are, for instance: coir, flax, hemp, sorghum panicles, chopped straw, reeds (should be pounded or split in order to break the cane walls and obtain thin fibres or ribbons), palm leaves, agave leaves and papyrus stalks (pounded and scratched to separate the pulp from the fibres), bamboo stripes, wood shavings, etc. Old jute sacks (the ones used for packing potatoes, coffee, etc) or woven fibre mats can be plastered with cement and piled until reaching the desired thickness, but the said materials may not be available everywhere. Some cactus species (for instance cardoon and prickly pear) have strong fibres embedded in their pulp, which are suitable for our scope.

Photo 4: panel of vegetal fibre agglomerated with cement.

In any case, the walls and roof should be smoothed with light mortar and painted with lime on both sides. The scope is hygienical (the high alkalinity of lime prevents most pathogens to grow on it), aesthetical (white surfaces give the idea of cleanness), and bioclimatic too (the high reflectivity of the lime will keep the inside of the restroom fresher and more comfortable). The measures of each panel are shown in Drawing 1, section *Supporting Information and Drawings*. The assembly of the panels is shown in Drawing 2. The method for producing the panels is described in Annex 1.

Stability in high winds

The Challenge has not considered this aspect, nor is it specified in the EN 16194 standard, for the simple reason that cyclones are extremely rare events in Europe. Nevertheless, the Solver checked the stability in the worst case (empty superstructure, i.e., without the interface and any other fitting), finding it is stable in winds up to 13.4 m/s (48 km/h). Average monsoons are in the order of 6 m/s, so the structure is safe to install in most areas. If necessary, the superstructure can be secured in order to resist Category 1 hurricanes. The calculations are presented in Annex 2.

Privacy and other requirements

The annex file Drawing 2 shows the assembly procedure of the superstructure. Although steel angle plates and screws are more expensive than other components (for instance wood pegs or steel wire), their use makes the assembly straightforward and more robust in the case of wood-cement panels. On the contrary, if *cannucciato* panels are the choice, stitching the panels with steel wire along the joints will provide a better repartition of the mechanical stress. The inclination of the roof and the gap between it and the top of the walls is not critical. It is necessary to leave a gap just for natural lighting and ventilation (see example in figure 2). It is highly advisable to close the said gap with a mosquito net or a perforated metal plate, or even gauze bands, to prevent the entry of insects.

The EN 16194 norm requires that the locking system allows seeing from the outside if the restroom is occupied or free (for instance a dial with red/green sectors, which are visible depending on the position of the lock). Such feature can be included if desired, but in the opinion of the Solver it is not mandatory in the private environment. The simplest and cheapest (near-null cost) door locking system is shown in Drawing 3. If the string is secured on the outside lateral peg, the door is locked to prevent rats or other pests entering the restroom, or the doors slamming in the wind but, of course, the place is free. If the string is not visible from the outside, this means that the restroom is occupied because the user has secured the string to the inner lateral peg, and it is not possible to open the door from the outside.

Cost calculation of the proposed superstructure, normal and hurricane-resistant versions

N.B. the cost of the hurricane-resistant version is the maximum of two possible alternatives. The structure can be ballasted for free, just gathering stones or preparing sandbags and placing them on the base panel portion that protrudes outside the walls and/or on the roof. In the case of the guyed superstructure, nothing prevents employing wooden poles deeply planted in the ground (in most cases available for free on site) instead of steel stakes, in which case the cost is only a few cents for the steel wire.

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Vegetal fibres (kg)	78,65	0	$ -	65% of the panel's weight, density of the panel 10 - 11 kg/m2, 11 m2 necessary
Portland cement (panels plus plastering, kg)	44,4675	4	$ 4,81	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.)	14		$ 4,20	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
Galvanised steel screws for wood , 20 mm, M4.8 (kg)	1	100	$ 2,70	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Spent lime for painting (kg)	5	3	$ 0,41	Price in Ethiopia not available, assumed 75% of the price of Portland cement
Door Hinges (pcs)	3	25	$ 2,03	https://con.2merkato.com/prices/material/7/601
Ventilation fine wire mesh (m2)	0,6	150	$ 2,43	https://con.2merkato.com/prices/material/7/798
Total Material Cost, basic superstructure			**$ 16,57**	
If installed in areas with risk of hurricane (119 km/h windspeed), additional cost for bracing				
Galvanised wire 2.5 mm diameter (guys)	0,5	34	$ 0,46	price per kg https://constructioninethiopia.com/construction-materials-in-ethiopia/
Stakes for the guys (4 x steel bars 20 mm x 400 mm, 1 kg each, unit price in ETB/kg)	4	38,8	$ 4,19	https://con.2merkato.com/prices/material/2/31
Total material cost for guys and stakes			*$ 4,65*	
Total material cost , braced superstructure			**$ 21,23**	

** Excel file with the calculation formulas and links to the information sources included.*

2) Interface

The reference norm accepts both squatting slabs and sitting bowls as user interfaces. The preference for one or the other is mainly cultural. The Solver provides both solutions, including a support for people with "mild motorial disability" (pregnant women, elders, etc.) in the case of the squatting slab. In all cases, the Solver assumed anal cleansing with toilet paper or any other dry wipe. Hence, the box for collecting the faeces needs to contain just 2 – 5 cm of litter covering the bottom, the minimum to prevent the faeces sticking on it. Any dry and porous material should be able to fulfil the said function: sand, clay-loam soil, organic soil or compost, straw, cereal husks, chopped newspapers, etc. According to the reference, the minimum area for receiving the faeces is 180 x 180 mm (or a hole 180 mm diameter, figure 4 and its reference), the Solver assumed a box with inner measures 200 mm x 200 mm. The average volume of absorbent material contained in the box will be then 50 mm x 200 mm x 200 mm = 2 dm^3. The maximum volume of faeces and litter generated daily will be then 12 dm^3.

a) Squatting slab.

It is the simplest solution to build. The size of the slab and its holes are those recommended by the WHO, shown in figure 4. In this solution, a podium with the urine collection funnel and faeces collecting box replaces the slab with holes.

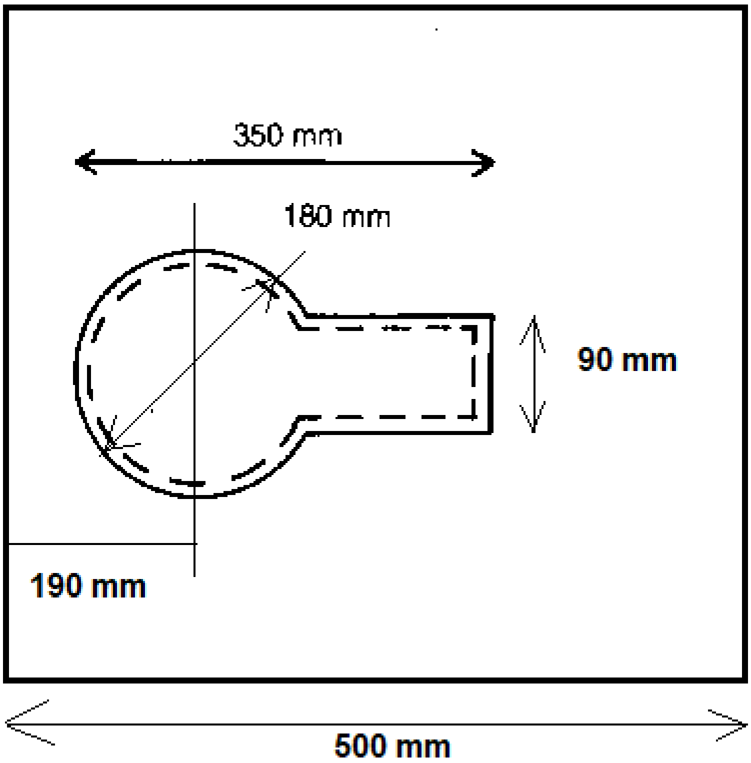


Figure 4: The minimum dimensions of a squatting pan (source (https://www.who.int/docstore/water_sanitation_health/onsitesan/ch04.htm). The urine diversion results from dividing the circular from the rectangular hole.

The norm EN 16194 establishes that the user's interface must have a flushing system actioned by a push-button, a pedal, a chain or string, or a lever. Extending the said prescription to the case of a dry toilet means that the box containing the used litter and faeces must have a mechanism allowing to dump the used litter out of the structure. In our case, the Challenge does not explicitly require the said function, but in a more general way it specifies that the solution must "facilitate safe management of faecal material". The purpose of including a "flush system" for dry litter in this solution is precisely complying with the said requirement. The proposed "flush system" is easy to implement it with a litter box hinged on the end adjacent to the back wall and a lever that tips it, dumping the used litter into the external vault (described in the next section), as shown in figure 5.

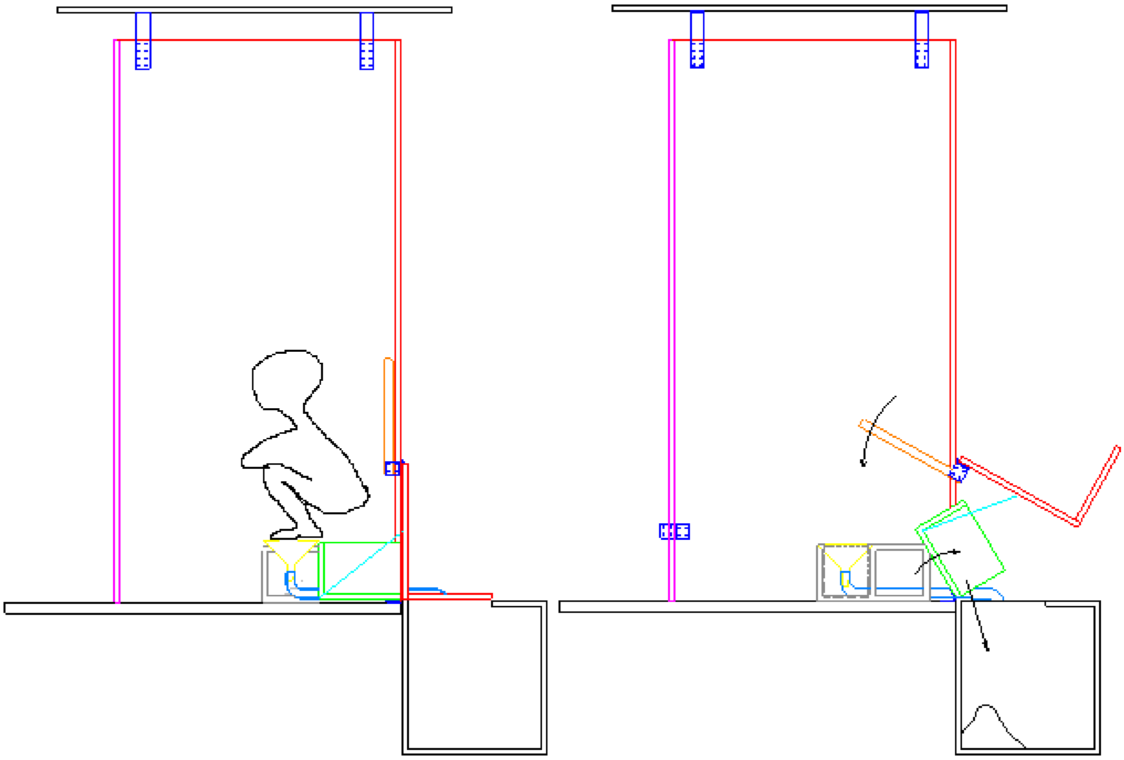


Figure 5: The proposed "flush system". The flap door keeps both the superstructure and the containment volume closed. The flap door is connected to a lever by means of a metal bracket, bolts or even steel wire. A wire or string connects the litter box and the flap door. The litter box is hinged to the floor. When pulling the lever, the string lifts the box, dumping its content into the now open containment volume.

The most straightforward way of making the tipping box is with wooden planks, 200 mm wide and 16 – 20 mm thick, joined with screws and finished with several hands of synthetic enamel for making the surface smooth and washable. The Solver analysed the cost of making the tipping box with stainless steel plate too. The said alternative seems to be economically more convenient, but stainless steel sheets may not be available everywhere for retail purchase. Of course, it is possible to recover the metal plate from a used a tin can but in this case probably the duration will be of 2-3 years. A compromise between durability and cost consists in making the tipping box with galvanised steel or aluminium plate -usually available as a retail item in hardware and construction materials shops. Making the tipping box with terracotta is another option, surely cheaper than purchasing a 4-m long wooden planks and discarding half of it, but requiring more handcraft skill. It is also possible to make a mould with an old carboard box and then make the tipping box as a single-cast block of light mortar. As an alternative, the same "*cannucciato*" technique proposed for the walls and floor of the superstructure is also suitable for the construction of a box with woven reeds or bamboo strips, lined with cement or cement-sand mortar, or with just 4 ceramic tiles. Rigid plastic boxes of adequate size (roughly 20 x 20 x h=10-15 cm) can be found in every town's hardware or household shop. It is easy to cut away one side of the box and fix it with wire or screws to the hinge. A cost estimation of this alternative is provided too.

Drawing 4 shows the corresponding mechanism for tipping and emptying the box after each use and the flap door that keeps the toilet's interior separated from the outside and opens only when dumping out the used litter. Drawing 5 shows the measures of the litter box. Please observe that the litter box and the urine sink are two separated items installed between two concrete blocks. The size of the standard blocks is enough to make them suitable as the pedestals to squat on, making unnecessary the production of a slab. A plastic funnel inserted in a flexible PVC garden pipe makes the simplest and cheapest device for collecting the urine and conveying it to the storage (discussed in the section corresponding to the vault). The operation sequence is:

i. Fill the box with absorbent material.

ii. Squat on the brick pedestals and defecate.

iii. Pull the handle or lever to tilt the box and dump its content outside of the toilet and into the containment system.

iv. Accompany the lever back to bring the box to its normal position.

The Solver envisaged installing two support handles for the users that may have some difficulty to squat, like elders or pregnant women. The idea of using rope instead of rigid handrails results from checking references [xv] and [xvi], deeming the steel pipe handrails more adequate as a support for people moving on a wheelchair. The support handles made with ropes are the easiest and cheapest option for providing extra stability and the user can easily adjust the length of the rope according to his/her size and weight. Lacking information on the price of ropes, the cost of the handles was assumed as a lumpsum 0.50 US$, since it only requires 1 to 2 m of rope (5 to 10 mm diameter should be enough) and two pieces of plastic tube or a section of bamboo culm, 150 – 200 mm long, in order to provide a more comfortable grip than holding oneself to the bare rope.

The table below shows the cost analysis of the different construction solutions.
N.B.: the cost of the solution with a tipping box made of timber painted with synthetic enamel is the highest because in the assumed market it would be necessary to purchase a plank 4 m long and a tin of 1 kg paint, using only half of the timber and a small quantity of paint.

Material	**Qty. Required**	**Local Unit Cost (ETB)**	**Cost (US$)**	**Source and remarks**
Steel sheet, 0,25 mm thick	**0,24**	269	$ 1,74	Metal Sheet - G32 CIS - 0.25mm Thickness, price per m2, https://con.2merkato.com/prices/material/7/777
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	2	15,6	$ 0,84	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Flat mending plates, galvanized steel	2		$ 0,60	Assumed the same price of the angle brackets
3 m rope or steel wire and 2 pieces of plastic tube or bamboo for the holding handles and tipping litter box			$ 0,50	lumpsum estimation
Total Material Cost, box made of steel sheet			**$ 6,40**	

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Stainless steel plate , 0,3 mm thick , for the litt	1,4		$ 4,20	3 US$/kg https://www.steelplates.in/suppliers/eritrea/stainless-steel-sheets-plates-in-ethiopia/
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	2	15,6	$ 0,84	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Flat mending plates, galvanized steel	2		$ 0,60	Assumed the same price of the angle brackets
3 m rope or steel wire and 2 pieces of plastic tube or bamboo for the holding handles and tipping litter box			$ 0,50	lumpsum estimation
Total Material Cost, stainless steel box			**$ 8,85**	

Plastic box				
Material	**Qty. Required**	**Local Unit Cost (ETB)**	**Cost (US$)**	**Source and remarks**
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	2	15,6	$ 0,84	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Rigid plastic box, approx 20x020x30. One end must be cut away to allow dumping on tipping	1		$ 1,95	Prices in Ethiopia non available. Two examples of suitable articles available for online purchase in South Africa and from a Turkish producer https://www.game.co.za/game-za/en/All-Game-Categories/Home-%26-Garden/Storage-%26-Organising/Storage-Boxes/Clear-%26-Colour-Plastic-Totes/Big-Jim-4L-Storage-Box-Clear-STORAGE-BOX/p/729973-EA and https://www.eurometall.com.tr/en/opened-front-plastic-box-20x20x30-cm
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Flat mending plates, galvanized steel	2		$ 0,60	Assumed the same price of the angle brackets
Lever for dumping the tipping litter box			$ -	Assumed that a wooden stick can be collected anywhere, no need to purchase
3 m rope or steel wire and 2 pieces of plastic tube or bamboo for the holding handles			$ 0,50	lumpsum estimation
Total Material Cost, rigid plastic box with one end cut away			**$ 7,54**	

Box made with fibre-cement, plastered with thin mortar				
Material	**Qty. Required**	**Local Unit Cost (ETB)**	**Cost (US$)**	**Source and remarks**
Portland cement (kg)	1,5	4	$ 0,16	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	2	15,6	$ 0,84	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Lime and sand for mortar			$ 0,50	The quantity is so small that a lumpsum in excess was arbitrarily defined
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Flat mending plates, galvanized steel	2		$ 0,60	Assumed the same price of the angle brackets
Lever for dumping the tipping litter box			$ -	Assumed that a wooden stick can be collected anywhere, no need to purchase
Super synthetic enamel	1	165	$ 4,46	https://con.2merkato.com/prices/material/10/896
3 m rope or steel wire and 2 pieces of plastic tube or bamboo for the holding handles			$ 0,50	lumpsum estimation
Total Material Cost, fibre-cement box			**$ 10,60**	

Seat and tipping box made with white ceramic tiles, 20x20 cm				
Material	**Qty. Required**	**Local Unit Cost (ETB)**	**Cost (US$)**	**Source and remarks**
Box made with 20x20 Ceramic tiles (m2)	**0,16**	400	$ 1,73	https://con.2merkato.com/prices/material/8/135
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	4	15,6	$ 1,69	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
white 20x20 ceramic tiles (m2) instead of seat	**0,2**	400	$ 2,16	https://con.2merkato.com/prices/material/8/135
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Total Material Cost, tipping litter box made w/ceramic tiles , plastic funnel for urine diversion, plastic toilet seat			**$ 9,73**	

Box made with timber planks, enamelled with synthetic paint				
Material	**Qty. Required**	**Local Unit Cost (ETB)**	**Cost (US$)**	**Source and remarks**
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	2	15,6	$ 0,84	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Timber 2.5cmX20cmX400cm - Ethiopian Shashemene. One plank for the litter box and flapping door, and 1.6 m will still remain	1	300	$ 8,11	https://con.2merkato.com/prices/material/5/357
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Flat mending plates, galvanized steel	2		$ 0,60	Assumed the same price of the angle brackets
Lever for dumping the tipping litter box			$ -	Assumed that a wooden stick can be collected anywhere, no need to purchase
Super synthetic enamel	1	165	$ 4,46	https://con.2merkato.com/prices/material/10/896
3 m rope or steel wire and 2 pieces of plastic tube or bamboo for the holding handles			$ 0,50	lumpsum estimation
Total Material Cost, painted timber box			**$ 18,16**	

b) Sitting bowl

Sitting bowls are more suitable where one of the family members has a more severe disability, preventing him/her to squat (e.g., victim of poliomyelitis, amputated leg, obese individual). Photo 7 shows a plastic sitting bucket employed for camping. The Solver adopted the measures of this product as a model for developing further the squatting pedestal with tipping litter box described above. The solution is exactly the same as the one described for the squatting pedestal, with the only difference that instead of 2 hollow concrete bricks the pedestal in this case has 4, with the seat hinged on top of it. The seat is made with the remaining of the timber plank employed for building the tipping litter box, if the said solution is adopted, or can also be a commercial toilet seat. If making the tipping box with timber, plenty of white synthetic enamel will be left after painting it.The remaining enamel can be then employed for coating the seat with several hands, in order to provide a smooth, water-repellent, easy to clean surface. If the tipping box is made with steel sheet or cement, then the seat can be a standard toilet seat (prices in Ethiopia not available, the Solver could only find the retail prices in South Africa https://www.builders.co.za/Bathroom/Toilets-%26-Toilet-Accessories/Toilet-Seats/c/Toilet%20Seats).

The operation sequence is:

i. Lift the seat.

ii. Fill the box with absorbent litter.

iii. Lower the seat and defecate.

iv. Pull the lever to tilt the box, so that it dumps the used litter out of the toilet, into the containment system.

Photo 5. The measures of a portable WC for campers were employed as a minimum benchmark for developing this solution. Source: https://www.ebay.it/i/173804888196?chn=ps&norover=1&mkevt=1&mkrid=724-128315-5854-1&mkcid=2&itemid=173804888196&targetid=884331517139&device=c&mktype=pla&googleloc=1008960&poi=&campaignid=9556813883&mkgroupid=103744186728&rlsatarget=pla-884331517139&abcId=1145978&merchantid=116410117&gclid=Cj0KCQjwxNT8BRD9ARIsAJ8S5xarfNehIz03HYwseHc4P3mJX6UzEL5koUC14UHKM01A21AkIZvyuwMaAg5cEALw_wcB

Drawing 6 shows the construction of the seat, the urine collection funnel and the tipping box mechanism. The acceptable range for the height of the seat (comparing several models of commercial sitting bowls and camping buckets) is 350 – 420 mm. In our case the height is 400 mm because 200 mm is the standard thickness of the hollow concrete blocks. If a lower seat is desired (e.g. if there are small children in the family) it is possible to employ 3 blocks of 200 mm and 3 of 150 mm, reaching 350 mm. The cost is almost the same as in the case of the squatting pedestal, the only additional materials required are: two hollow concrete blocks, two hinges and two steel mending plates (if making the seat cover with the left wooden plank) or a standard plastic seat. Eventually, the seat can be omitted, lining the concrete base with white ceramic tiles in order to provide a smooth and easy-to-clean surface, though the feel is not as comfortable as with a standard plastic seat.

The cost analysis of the different construction alternatives is shown below.

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Steel sheet, 0,25 mm thick	**0,24**	269	$ 1,74	Metal Sheet - G32 CIS - 0.25mm Thickness, price per m2, https://con.2merkato.com/prices/material/7/777
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	4	15,6	$ 1,69	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Plastic toilet seat	1	49 RD	$ 3,23	Price in South Africa from https://www.builders.co.za/Bathroom/Toilets-%26-Toilet-Accessories/Toilet-Seats/Wirquin-Bathroom-Basics-Neon-Lite-Toilet-Seat---White-%28452-x-380-x-38mm%29/p/000000000000648091
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Total Material Cost, tipping litter box made of galvanised steel , plastic funnel for urine diversion, plastic toilet seat			**$ 10,81**	

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Stainless steel plate , 0,3 mm thick , for the litter box and urine funnel (kg)	1,4		$ 4,20	3 US$/kg https://www.steelplates.in/suppliers/eritrea/stainless-steel-sheets-plates-in-ethiopia/
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	4	15,6	$ 1,69	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Plastic toilet seat	1	49 RD	$ 3,23	Price in South Africa from https://www.builders.co.za/Bathroom/Toilets-%26-Toilet-Accessories/Toilet-Seats/Wirquin-Bathroom-Basics-Neon-Lite-Toilet-Seat---White-%28452-x-380-x-38mm%29/p/000000000000648091
Total Material Cost, both tipping litter box and urine funnel made of stainless steel, plastic toilet seat			**$ 11,83**	

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	4	15,6	$ 1,69	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Timber 2.5cmX20cmX400cm - Ethiopian Shashemene. One plank is enough for the litter box , flapping door, and seat	1	300	$ 8,11	https://con.2merkato.com/prices/material/5/357
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
Lever for dumping the tipping litter box			$ -	Assumed that a wooden stick can be collected anywhere, no need to purchase. Eventually, it can be made with the remainings of the timber plank
Super synthetic enamel	1	165	$ 4,46	https://con.2merkato.com/prices/material/10/896
3 m rope or steel wire and 2 pieces of plastic tube or bamboo for the holding handles and tipping litter box			$ 0,50	lumpsum estimation
Total Material Cost, tipping litter box and flapping door made of painted timber			**$ 18,40**	

Seat and tipping box made with white ceramic tiles, 20x20 cm				
Material	**Qty. Required**	**Local Unit Cost (ETB)**	**Cost (US$)**	**Source and remarks**
Box made with 20x20 Ceramic tiles (m2)	**0,16**	400	$ 1,73	https://con.2merkato.com/prices/material/8/135
Portland cement (kg)	1	4	$ 0,11	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x200	4	15,6	$ 1,69	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
HDPE pipe 1/2" for the urine (m)	2	7	$ 0,38	https://akerabi.com.et/product/hdpe-pipe-1-2/
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,1	100	$ 0,27	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanized steel angle brackets 50 x 50 x 38 x 1,8 (pcs.) - Support for the lever	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
hinges for the litter box and flap door (pcs)	2	25	$ 1,35	https://con.2merkato.com/prices/material/7/601
white 20x20 ceramic tiles (m2) instead of seat	**0,2**	400	$ 2,16	https://con.2merkato.com/prices/material/8/135
Plastic funnel for collecting the urine	1	800 CFA	$ 1,44	Price in Ethiopia not available, reference from Benin https://www.psi.org/2020/06/covid19-handwashing-stations/
Total Material Cost, tipping litter box made w/ceramic tiles , plastic funnel for urine diversion, seat made with ceramic tiles			**$ 9,73**	

As in the case of the squatting pod, the stainless steel construction is potentially cheaper and more durable, but probably not available as a retail product. The solution with tipping box and seat made of enamelled timber costs practically the same as the equivalent solution of the squatting pod, because under the assumed market conditions it is necessary to buy at least 4 m of timber and 1 kg of paint. The alternative with tipping box made of steel sheet and plastic toilet seat seems the best compromise. Some periodical maintenance will improve the durability of the steel sheet box to 10 years or more. If rust begins to form, just remove the tipping box, spread the rusty surface with used cooked oil of animal fat, and burn it on the fire. The said process is called seasoning (https://en.wikipedia.org/wiki/Seasoning_(cookware)) and provides a black finishing with improved resistance to corrosion.

c) Hands washing, menstrual hygiene

A basin for hands washing is mandatory if the toilet must be fully compliant with EN 16194, as it is the intention of the Solver (see example of fully compliant WC in photos 1 and 2). Since hands washing is an optional feature in the definition of the challenge, the Solver proposes a collection of different alternatives and their cost analysis, when this is possible, in Annex 3.

The superstructure's size is big enough to allow placing a tin, bucket, basket or any other container already available on site for disposing menstrual hygiene items. In case of adopting the gasifier stove as a means of recovering energy from the used litter (see the corresponding section), used menstrual diapers or nappies can be discarded in the tipping box and dumped in the containment vault, since the high temperature of gasification will safely destruct them. The suggested position for the waste bin and hands washing basin is shown as dotted lines in Drawing 4.

Some solutions for hands washing seem to be widely spread in Africa, like the "tippy tap" (https://iycf.advancingnutrition.org/keywords/tippy-tap) and its numberless variations. They will not be evaluated here, since they are essentially free. Solutions implemented in Benin and Ivory Coast cost for public use, as a response to COVID 19, cost about 12 US$ (https://www.psi.org/2020/06/covid19-handwashing-stations/).

The cost of including a simple hands-washing station and recovering the water to employ it together with the urine in the farm, is in the range 0.25 – 1.26 US$.

The Solver's low-cost alternative to the SATO Tap and Happy Tap, suggested as "desirable" by the Challenge's definition, is a plastic bottle or jerrycan, with a simple modification to turn its cap into a foot valve (figure 7). By pushing the bolt upwards, the washer will detach from the rubber O-ring, opening the hole in the plastic cap and allowing the water to flow. A rubber O-ring ensures that the weight of the bolt, nuts and washer assembly, plus the small pressure of the water column, are enough to keep the valve closed. The cost of the bolt, nuts and O-ring is probably less than 0.5 US.

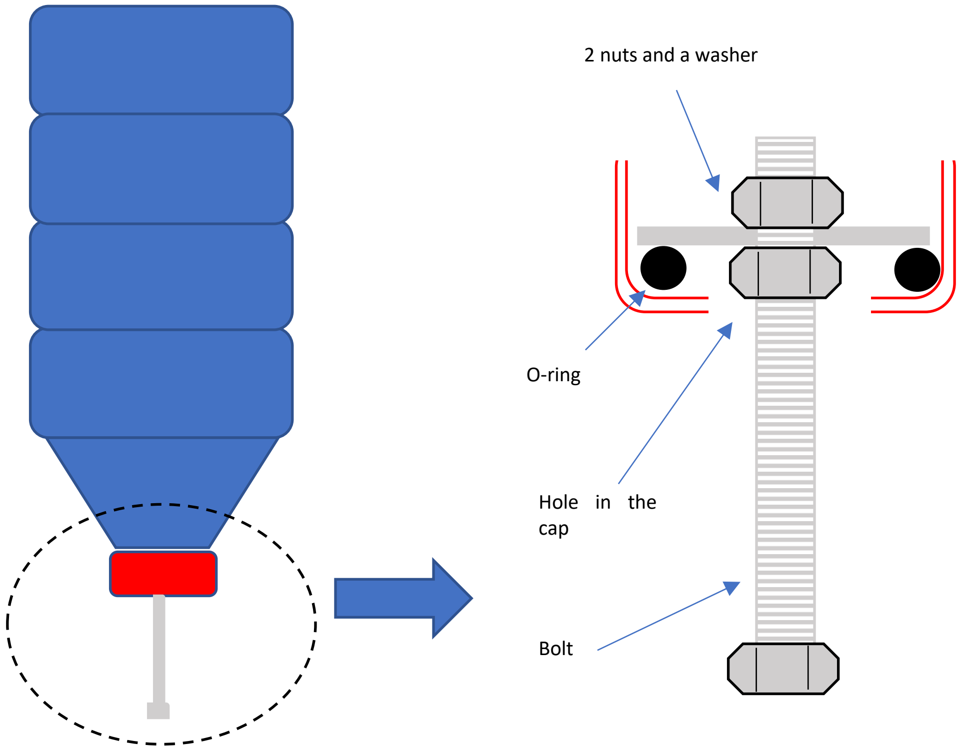


Figure 6. Forming a foot valve with the cap of a capsized plastic bottle or jerrycan

3) Containment system or vault

Since the Solver chose separating the faeces from the urine for the reasons already explained, the containment system must consist of two sub-systems, one for each waste flow.

3.1- Faeces vault

As shown in Drawings 4 and 6, the "tipping litter box" dumps the mixture of faeces and litter into a generic "box", represented by a dotted rectangle placed outside of the superstructure. The Solver decided to design a containment system outside of the superstructure instead of directly beneath it (as it is customary for pit latrines and compost vaults), for the following reasons:

a) preventing odours (the experiences reported by ref. [viii] demonstrate that odours are unavoidable if the pit or composting system is placed beneath the squatting slab or seat, unless there is a fan constantly keeping the vault at a lower pressure than the environment);

b) avoiding the superstructure being placed on a pit, because it would be then necessary to spend extra money providing some kind of reinforcement to the walls of the latter, otherwise the earth could collapse and damage the superstructure or put the user in danger;

c) avoid installing the superstructure on some kind of platform and collecting the waste in a bin or any similar container, a frequent configuration in the consulted literature, that would increase the construction cost beyond the limits imposed by the Challenge;

d) eliminate the need of moving the superstructure to a new pit each time that the pit in use is full;

e) making easy and more tolerable the job of emptying the bin or pit when it is full of litter.

There are two possible alternatives for implementing such a containment system:

a) "Passive" collection vault. It is the concept envisaged in the Challenge's requirements, and the one more largely adopted in most of the sanitation projects described in the literature. In summary, the specifications of the Challenge for such a containment system are: "2 m^3 total volume", which must be: "emptiable by a mechanical vacuum tanker" (not applicable to our case); or "removable from the ground such that the waste can be left in the ground to decompose while an alternative place for containment is used and the toilet moved"; or "otherwise facilitate safe management of faecal material", and "Able to support the weight of anything above it such as people or structures".

b) "Active" collection and quick sanitation. This alternative concept means that the containment volume will be small, and the treatment very quick, leaving an inert residue (no odour, no pathogens, dry) which can be safely employed as soil conditioner or stored for later use, or even re-used as absorbent litter in the toilet, or as fuel to reduce firewood consumption.

3.1.1- Passive collection and dehydration vault

Please note that, as explained in the section "Interface", under the assumed operation conditions the total amount of absorbent litter and faeces produced daily is 12 dm^3. Hence, the volume defined by the Challenge will be full in 166 days i.e. 5.5 months. Please also note that the ratio of absorbent material to faeces (in volume) is nearly 12:1.2 (see assumption *n)* and description of the tipping box in section "Interface", average density of straw = 50 kg/m^3, from https://www.gumtree.co.za/s-1+ton+bulk+bags/v1q0p1). Absorbent materials like straw, dry clay or soil, etc. usually have a moisture content of about 10%. The faeces have 50%. In the worst case (nearly hermetic vault, no entry of external moisture but no evaporation either) the equilibrium moisture of the mixture will be:

$M = (10\% \times 12\ dm^3 \times 0{,}050\ kg/dm^3 + 50\% \times 2.4\ kg) / 3\ kg = 42\%$

In order to obtain a substrate that is microbiologically inert and safe, it is necessary to bring the overall moisture below 13%, i.e., it is necessary to allow air to circulate and/or add ash or quicklime (OCa) to the absorbent material, because the formation of hydroxides (spent lime $Ca(OH)_2$) will capture water for the reaction. Since the said materials may not be available / affordable in the necessary quantities (nearly 1.5 kg/day of quicklime to neutralize half of the water and bring the overall moisture under 13%), it is necessary to include in the vault some ventilation holes and a ventilation pipe, or make the containment envelope porous in order to allow for free air circulation, or include a biofilter, but in this case it is necessary to sprinkle it with water from time to time in order to keep its biological activity at the optimum rate. Only the cover must be impervious in order to prevent the rain moistening the soil and the content of the pit. The said considerations lead the Solver to analyse the following construction alternatives:

1) Containment box, 2 m^3, made of pervious concrete, impervious cover made of fibre-cement panel plastered with lime-cement mortar, PVC vent pipe.
   The dimensions of the box are 2 m length x 1 m width x 1 m depth, the thickness of the bottom and side walls is 5 cm (pervious concrete), the cover is made with two panels of fibre-cement, 1 m x 1 m x 4 cm thickness, plastered with lime-cement mortar to make them impervious to rain. In order to build the box, it is necessary to dig a pit 2,10 m x 1,10 m x 1,10 m. Assuming the worst local conditions (buying gravel because coarse aggregates are unavailable on site), and the recipe of pervious concrete provided in the following website https://www.perviouspavement.org/materials.html, the construction cost is 21,13 US$, as shown in the following cost analysis:

Material cost, pervious cement box 2m x 1 m x 1 m, 5 cm thick, cover fibre-cement panel	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Vegetal fibres (kg)	7,15	0	$ -	65% of the panel's weight, density of the panel 10 - 11 kg/m2, 3 m2 necessary
Portland cement (cover panels plus plastering, kg)	9,8	4	$ 1,06	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Spent lime for waterproof mortar (kg)	0,2	3	$ 0,02	Price in Ethiopia not available, assumed 75% of the price of Portland cement
Sand (for waterproof mortar, dm3)	1,5	0,7	$ 0,03	https://con.2merkato.com/prices/material/2/21
Portland cement for pervious concrete 1300 kg/m3,(kg)	104	4	$ 11,24	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Gravel 4 - 19 mm (m3)	0,4	600	$ 6,49	https://con.2merkato.com/prices/material/2/23
Rigid PVC ventilation pipe diam. 50 mm , 3 m pc.	1	85	$ 2,30	https://constructioninethiopia.com/construction-materials-in-ethiopia/
Total			$ 21,13	

2) Containment in "jumbo bags" (aka big bags, bulk bags, ton bags). It is difficult to estimate the cost because the web sources show an enormous variability: from 15 € (online purchase in Europe), to 2.75 US$ in India. For the purpose of this analysis, the Solver assumed the cost in South Africa, 50 Rand (3.25 US$). This solution is probably the simplest and easiest to manage. It is necessary to dig a pit about 2,50 m long, 2,50 m wide and 2,30 m deep. Two jumbo bags, A and B, are hanged from 4 wood or bamboo poles stretching across the pit, avoiding any contact with its walls and bottom in order to allow air to circulate freely. When bag A is full, it is moved to the outer position in the pit and bag B is placed to receive the litter from the toilet. Please note that, if only straw, ash, charcoal bits or similar absorbent litter is employed, the full bag will weigh about 50 - 60 kg, so two men can easily lift and reposition it. Once bag B is full, bag A is dumped in the farm and replaces bag B, which is moved to the outer part of the pit to finish the maturation of its content. The cost a of this solution under the worst conditions (wooden or bamboo poles of the necessary diameter must be purchased because unavailable on site) is nearly half of the former solution. If the support poles can be collected on site for free, then the total cost is only 4.35 US$. Also note

that the vent pipe is not necessary in this case: since the bags are hanging inside a pit with plenty of room for the air to circulate around (no contact point with the floor or the walls) the aerobic bacteria in the soil will easily capture and digest any VOC (volatile organic compound) diffusing from the litter until the faeces are dry. If necessary, (field trials recommended) the biofilter effect can be boosted by placing a layer of straw, charcoal scraps, dead leaves, wood chips or any other loose biomass on the pit's cover, keeping it moist. If available, peat is also an excellent material for biofilters as long as it is kept moist. In the opinion of the Solver it will not be necessary to place a biofilter, but he included it in Drawing 10, just in case.

Material cost, jumbo bags, cover with fibre-cement panel	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Vegetal fibres (kg)	7,15	0	$ -	65% of the panel's weight, density of the panel 10 - 11 kg/m2, 3 m2 necessary
Portland cement (cover panels plus plastering, kg)	9,8	4	$ 1,06	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Spent lime for waterproof mortar (kg)	0,2	3	$ 0,02	Price in Ethiopia not available, assumed 75% of the price of Portland cement
Sand (for waterproof mortar, dm3)	1,5	0,7	$ 0,03	https://con.2merkato.com/prices/material/2/21
Second hand bulk bag South Africa	2	30 - 50 ZAI	$ 3,25	https://www.gumtree.co.za/s-1+ton+bulk+bags/v1q0p1
Eucalyptus poles, 4 m long, 50 mmm diameter	4	65	$ 7,03	https://con.2merkato.com/prices/material/4/68
Total			**$ 11,38**	

3) Shallow trench covered with three fibre-cement panels, frequent raking.
This is a possible solution where the ground is rocky or anyhow difficult to dig, or where the soil is too sandy and digging a pit with vertical walls is impracticable. A trench with V-shaped walls at 45° or less provides enough stability for most common soils. For extremely sandy or wet soils, the angle of repose is about 30° (https://alchetron.com/Angle-of-repose), so the trench should be shallower and longer. A shallow trench provides a big area of contact between the litter and the soil's bacteria. Managing it requires nevertheless more manual work, since it will be necessary to shift the litter that accumulates under the tipping box of the interface towards the opposite end of the trench, until this one is full. The advantage is that with this system the treatment is a "continuous process" instead of "batch" (like in the jumbo bags concept). The litter accumulated on the far end of the trench is the oldest and the user can collect it when necessary for fertilizing the farm all the year round. Assuming that the trench is 4.2 m long, 1.2 m wide and 0.56 m deep, with a 45° trapezoidal section, the volume is exactly 2 m^3. The cover will require 3 panels like the ones employed for the base of the superstructure (1.41 x 1.41 m), which can withstand the weight of an adult. Once a week, the user should push the fresh litter to the end with a rake. Like in the former case, a vent pipe is probably unnecessary, because of the large absorption area of the soil and the biofilter effect of the soil bacteria, but experimental data from the field are needed. The cost is only 3.96 US$ without vent pipe, and rises to 6.42 US$ in the worst case, in the eventuality that a vent pipe is required. A shallower, V shaped trench (2 m wide x 0,5 depth) will require a bigger cover, the cost rising to 6.42 US$.

Material cost, 45° trapezoidal section trench , cement-fibre cover	Qty. Required	Unit Cost	Cost (US$)	Source and remarks
Trench (1.2 m upper width, 0,56 m bottom width, 0,56 m deptht x 4.2 m long = 2 m3)				only labour, no lining because the 45° slope is stable enough in most soil types
Portland cement (3 covers 1.4x1.4m x 40 mm + waterproof mort	36,2	4	$ 3,91	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
vegetal fibres for the panels (kg)	79,2			assumed free
Spent lime for waterproof mortar (kg)	0,2	3	$ 0,02	Price in Ethiopia not available, assumed 75% of the price of Portland cement
Sand (for waterproof mortar, dm3)	1,5	0,7	$ 0,03	https://con.2merkato.com/prices/material/2/21
Total			**$ 3,96**	

Material cost, V-shaped trench, cover with fibre-cement panel	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Vegetal fibres (kg)	57,2	0	$ -	65% of the panel's weight, density of the panel 10 - 11 kg/m2, 8 m2 necessary
Portland cement (cover panels plus plastering, kg)	37,2	4	$ 4,02	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Spent lime for waterproof mortar (kg)	0,5	3	$ 0,04	Price in Ethiopia not available, assumed 75% of the price of Portland cement
Sand (for waterproof mortar, dm3)	3	0,7	$ 0,06	https://con.2merkato.com/prices/material/2/21
Rigid PVC ventilation pipe diam. 50 mm , 3 m pc.	1	85	$ 2,30	https://constructioninethiopia.com/construction-materials-in-ethiopia/
Total			**$ 6,42**	

3.1.2- Active collection and quick sanitation

The solutions proposed above are alternatives that meet the Challenge's request to foresee at least 2 m^3 of maturation volume in order to stabilize the faecal matter. In the opinion of the Solver, the Seeker has not considered that:

- Even after one year of maturation, there is still some probability that some pathogens may survive and re-activate months later, when they come again in contact with the wet soil.
- Digging a 2 m^3 pit is a hard work, especially in tropical climate.
- Digging such a pit may not be practicable everywhere, if the soil is too rocky, or too sandy or too muddy.

The only treatment that ensures 100% destruction of any pathogen is a thermal shock. Temperatures between 62°C and 74 °C for two hours will kill most pathogens (according to https://www.cdc.gov/foodsafety/keep-food-safe.html and https://www.who.int/water_sanitation_health/dwq/Boiling_water_01_15.pdf, Salmonella, E. Coli, Vibrio, Listeria, Campylobacter die in the said range). Ammonia, the main component causing the bad odour of excreta, separates from water and volatilizes at temperatures > 65°C. A thermal treatment has a short residence time which in turn makes a big vault volume unnecessary, potentially saving costs, or at least, minimizing the manual labour required for the construction. On the other hand, more frequent processing is required from the user, but the product of the thermal treatment has potentially a higher agronomic value (sterile organic matter as soil conditioner) or additional benefits, e.g. replacing firewood or dry cattle dung as fuel and providing biochar to improve the soil's fertility and contain the desertification. Having discarded the composting process for the reasonings in the first section, point m), the remaining alternatives are either the combustion or the solar dehydration at high temperature of the used litter and fresh faeces.
The first alternative may be more convenient in contexts where women need to walk long distances to get firewood for cooking. Replacing part of that wood with the litter will have a series of benefits, e.g.: less time and effort consumed, improved cooking efficiency on traditional cooking stoves or open-fires, less deforestation, no odour compared to the traditional combustion of dung (the stove burns the pyrolysis gas, not the biomass), the biochar residue has many benefits in improving the soil's fertility. Gasifier stoves require small size biomass, allowing the use of crops residues and easier-to-carry fuels (straw, husks, chopped reeds, split canes). The drawback of this alternative is cultural: volunteer's experience (ref. [xvii]) shows that it is necessary to provide some training both for the construction and the use of such stoves, and in spite of their many benefits, there is still some cultural resistance to change that hampers their wide diffusion.

The second alternative is more straightforward, since drying the litter and subsequently using it as soil conditioner in the farm poses no need for training of the users, but it requires the purchase of some materials and more skills. The limitation of such a solution is that it may not be adequate for rainy places.

The following calculations are based on the assumption that the toilet's tipping box described in the section "interface" dumps its content in a basket, a plastic or steel bucket or any available container with a handle (to avoid the direct contact with the litter), placed in a small pit (50 x 50 x 50 cm should be enough). One member of the family will collect the used litter and process it every day in any of the ways described below.

1) Using the litter as co-fuel in a gasifier stove for cooking.
   As reported in reference [x], in some countries the dry human faeces serve as fuel together with dry cattle dung. Hence this solution will be easily acceptable in such countries, though it may need some demonstration and promotion effort in countries where only firewood is employed as fuel and the idea of using litter from the toilet as fuel to cook may encounter some cultural resistance. The design and operation is explained in Annex 4.
   The cost estimation ranges from free (construction with stones and / or clay) to 3.50 US$ in the worst case (purchasing hollow concrete blocks):

Material cost, gasification stove	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Portland cement (kg)	0,5	4	$ 0,05	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Hollow concrete block 400x200x100	12	10	$ 3,24	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
sand	1	0,7	$ 0,02	https://con.2merkato.com/prices/material/2/21
2.5 mm steel wire (support for the pot, optional)	0,2	34	$ 0,18	price per kg https://constructioninethiopia.com/construction-materials-in-ethiopia/
Total			**$ 3,50**	

2) Solar thermal disinfection
   The Solar dehydration of the faeces is a technique that has already been applied in many sanitation projects. The basics of this concept are explained in ref. [xviii] and [xix] , although the models shown in both references have several flaws: the "solar box" seems underdimensioned, its ratio of collection area to volume is patently too low for an expert's eye, and the inclination is typical of a Northern Country hence, it is logic it won't perform well in tropical areas in spite of the higher irradiation. Furthermore, the text does not explain how to correctly dimension it. The Solver has already observed that some cooperants from Europe or the USA tend to propose solutions already tested in their home Countries or in other Countries, forgetting to adapt them to the local conditions, like latitude, climate, cultural factors, etc. The Solver will correct all those design flaws by providing a range of dimensions instead of the one-fits-all approach common in the literature. A correct dimensioning of the solar collector ensures both the sterilization of faeces at high temperatures (< 80°C at midday, <60°C during most of the daylight time) and their quick dehydration. A vent hole placed on the top or the back of the solar box will provide a draft current to evacuate the moisture and odorous substances by means of natural convection, no fan required. Dry faeces are stable and non-odorous as long as they are kept dry because no microbiological activity can proceed when the moisture is less than 13%. The dry excreta and absorbent material can be then safely and easily spread in the farm as a dry soil conditioner (it has only 20% of the nutrients contained in the human excreta, ref. [xiv] already cited, but provides carbon and water retention capacity to the soil, that's why it is important to recover it). Ash and charcoal rests are widely available in many rural areas where people cook with firewood. Adding them to the absorbent material employed as litter for collecting the faeces will furtherly improve the dehydration process and the quality of the dry soil conditioner (ref. [x] already cited). Considering that the present solution may be applied within the whole African continent, Latin American and Asian

Countries, comprised within the Equator and ±30° latitude, it makes sense to employ solar radiation for reaching the high temperatures required to sanitize the faeces, instead of expecting to reach that scope with the microbial metabolic heat of a composter. If correctly designed, solar boxes easily reach and exceed 100°C during at least 3 hours per day, by far more than enough for the sanitization of the excreta. The temperature is a second-order function of the mass and moisture of the box's content, it depends mainly on the design, the dimensions of the box and the concentrator, and the intensity of the solar radiation. Based on the references cited, faeces dried at t > 80°C are to be considered as an inert. The Solver assumes that the containment volume of 2 m^3 defined in the Challenge's rules is not necessary for this solution, since there's no need for providing a long-term storage of the dry faeces because they can be collected daily and once dried in the solar oven, it is safe to burn them as fuel or incorporate them to the farm's soil as dry manure.
The high temperature solar drier proposed in this section is essentially a "box solar cooker" (https://www.solarcookers.org/application/files/5915/7489/0133/Basics_solar_cooking_manual_.pdf) , dimensioned in such a way that all the faeces cumulated in one day will be dried at T>60° within the next day by means of solar radiation. The design procedure and construction sketch are included in Annex 5. The overall cost is 7.92 US$:

Material , solar concentrator	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Steel sheet, blackened with smoke, 0,25 mm thick	**0,7**	269	$ 5,09	Metal Sheet - G32 CIS - 0.25mm Thickness, price per m2, https://con.2merkato.com/prices/material/7/777
Insulation (straw, bark , cardboard bits, or any loose material)				assumed free
Glass window, 50x 50 cm, 3 mm thick	0,25	180	$ 1,22	https://constructioninethiopia.com/construction-materials-in-ethiopia/. U = 7.9 W/m2°C for single pane glass, horizontal, https://www.engineeringtoolbox.com/heat-loss-transmission-d_748.html).
Aluminium foil Roll 0,3 x 20 m = 6 m2	3 m2	1242 Nigerian Naira	$ 1,61	https://www.jumia.com.ng/generic-food-grade-kitchen-barbecue-aluminum-foil-rolls-household-baking-disposable-foil-packaging-length-5m-10m-20meters-width-30cm-thickness-20-microns-66400528.html
Cardboard to support Al foil concentrator and to build the solar box				assumed free, recycled box
Total			**$ 7,92**	

3.2- Urine collection and options for its use as fertilizer

The simplest way of providing 85 l of urine storage capacity (as calculated in assumption n) is buying 9 plastic containers with 10 l capacity, but the cost is difficult to estimate. A survey in the internet gave a market cost of nearly 1.89 US$ each jerrycan (online supplier in Uganda https://www.jumia.ug/other-10l-plastic-water-jerrycan-green-6696937.html), while it seems that in Benin and Ivory Coast the cost of the same jerrycan is just 500 CFA, i.e. 0.9 US$ each. A plastic barrel with 100 l capacity costs 350 INR (4.70 US$) in India (https://www.indiamart.com/proddetail/100-litre-plastic-barrel-17942795255.html) while Alibaba.com shows prices ranging from 10 to 60 US$ for the same item. Unless employing recycled 5-litre PET bottles or similar containers, it seems improbable to reach the necessary storage capacity for less than 10 US$.

Building a container of 50 x 50 x 50 cm (inner measures) with "*cannucciato*" of fibre cement, plastered with a thick layer of S-type mortar, will cost roughly 1.5 – 2 US$ of materials. Retrieving the mature urine without actually opening the lid of the container requires either a small hand pump (6 to 8 € online retail price https://www.ebay.it/itm/8mm-5-16-Fuel-Pump-Rubber-Hand-Fuel-Primer-Bulb-Gasoline-Pump-Petrol-Diesel/264286002730?_trkparms=ispr%3D1&hash=item3d88ac5e2a:m:mk3lEZ6a_L4HhGSWW0wgayg), or a cheaper syphon pump for extracting the liquid fertilizer and filling a bucket or jerrycan, but in this case it is necessary to dig a hole were to place the bucket at a lower level, to allow syphoning.

An alternative strategy to reduce the containment's cost is to avoid applying the urine directly to the soil at the plant's base, so no seasoning will be necessary. Indirect application via subsoil irrigation does not require any storage, is odourless and requires little or no handling of the urine. In this case, the urine will be collected in a 10 l plastic container and then distributed in the subsoil irrigation system every day. Valid subsoil irrigation systems are:

a) Buried clay pot irrigation. This traditional irrigation technique does not require the seasoning of the urine, it has been employed in Africa and Asia for millennia. It allows optimum irrigation with minimum consumption. The basics are explained in detail in reference [xx]. It will be necessary to make at least 36 clay amphoras or round pots with narrow mouth, each one with a clay lid, nearly 35 cm diameter (with 6-8 l capacity), plus 2 or 3 spare containers. Enamelled or glazed clay pots are not suitable because impervious, only porous terracotta is suitable. The 36 pots must be buried as directed in the reference booklet, distanced 1.5 m for the cultivation of corn, from 3 to 6 m for vine crops, or at intermediate distance for other crops. Each day, take a pot full with urine and add some to the water contained in each of the pots, no need to season the urine with this technique. The pots (a.k.a. "*ollas*" in the literature, from Spanish) can be cooked in an open fire or in a rudimentary kiln. Traditional pottery in Africa employs dry dung and crops residues as fuel. There's no need for reaching high temperatures, optimum porosity can be reached with 500 – 700°C. Directions on how to make suitable "*ollas*" can be found here: https://wateruseitwisely.com/olla-irrigation/.

b) Alternative to the above system. Instead of the clay pots, bury plastic bags (non-degradable ones, possible of thick plastic film for longer duration), fill them with sand or gravel and punch some holes in their surface. Every day, add into the sand-filled bags a mixture of water and urine, that will seep through the holes into the plant's root zone. The method is described in a FAO online booklet (http://www.fao.org/3/W3094E/w3094e05.htm).

c) Direct underground fertilization/irrigation with water and urine by means of clay pipes. There is plenty of literature on this water-saving method, mainly from India, Pakistan and Africa. One example is provided in ref. [xxi] . In this case, the urine collector and the eventual effluent from the hands washing station (eventually also mixed with the water collected from the shower and laundry, if present) must be connected to a network of porous clay pipes, buried at 30 – 50 cm depth. It will be necessary to form nearly 200 m of such clay pipes in order to cover the nearly 400 m^2 required for optimum application of the urine fertilizer to the crops (see assumption n). An experience in Zimbabwe is described in the FAO booklet cited above.

d) Porous cement pipes can be employed as an alternative to clay pipes, data on their application in South Africa can be found here: https://www.imesa.org.za/wp-content/uploads/2016/01/Concrete-Pipe.pdf but the Solver found no data on their cost. Directions on how to make pervious concrete can be found here: https://www.perviouspavement.org/materials.html and https://perviousproducts.com/make-pervious-concrete/. If fine gravel is available for free, making 200 m of 50 mm diameter porous pipes with 1 cm thickness will require 0,105 m^3 of cement, with a total cost of nearly 20 US$. Since this cost is in the same range of the plastic containers alternative, the Solver did not analyse further the pervious concrete option. Standard 200 mm concrete pipes are out of budget, since they cost 200 birr (5.40 US$ each, 2.5 m long, nearly 280 kg, https://akerabi.com.et/product/concrete-pipe-diameter-20-2/).

e) Used plastic bottles, 5 litres capacity, with a few holes punched at the bottom. Basically, it is equivalent to the alternative a) or b), but at zero cost if their collection is feasible.

The most straightforward option with the minimum labour and cost is then b) or e). Options a) and c) have a null material cost and provide a long use life, but require that the user invests manpower to collect the clay and the fuel, to manufacture the pipes or the pots and fire them. Assuming option b), the estimated cost for a plastic jerrycan and 90 – 120 polyethylene film bags (10 litre capacity) is in the range 2 – 10 US$. If sand or fine gravel is not available on site, then nearly 1 m^3 will be necessary for filling the plastic bags and the additional cost will be 700 birr = 18.9 US$ (https://con.2merkato.com/prices/material/2/21). A free alternative to sand can be the use of residual charcoal from cooking, since carbon is essentially inert and highly porous. Charred coconut or oil palm fruit shells, or bamboo cane sections are good alternatives to sand and fine gravel. In zones near to the sea, crushed seashells provide an excellent inert filler for the plastic bags.

The overall cost estimation of the different options that the Solver was able to analyse range from 3 US$ (option b described above) to 12.23 US$ detailed below.

Portland cement (kg) necessary for making a box of fibre cement panels, 50 cm side, 2 cm thick	6,6	4	$ 0,71	Price 400 ETB/quintal, https://con.2merkato.com/prices/material/2/18 . In Ethiopia 1 quintal = 100 kg because it was an Italian colony https://www.igi-global.com/dictionary/quintal/79340
Plastic jerrycan 20 l for transporting the urine to the farm	1	7300 UGX	$ 1,97	Price in Ethiopia not available, https://www.jumia.ug/nice-jerrycan-20-litre-yellow-89696.html
plastic syphon pump to fill the jerrycan from the urine container	1		$ 1,66	Price in South Africa https://www.superbuy.co.za/syphon-pump-manual-54cm.html
Total			$ 4,34	

Plastic jerrycans 20 l (collection, maturation and transport to the field)	5	7300 UGX	$ 9,86	tps://www.jumia.ug/nice-jerrycan-20-litre-yellow-89696.htm

Plastic jerrycan 5 l, punched holes, buried	20	15 INR	$ 4,20	https://www.indiamart.com/proddetail/white-5l-hdpe-jerry-can-21945972933.html
Plastic jerrycan 10 l (collection and daily transport to the field)	1	27 INR	$ 1,05	https://www.indiamart.com/proddetail/10-l-white-hdpe-jerry-can-21974082062.html?pos=10&kwd=10+litre+plastic+can&tags=A%7C%7C%7C%7C7539.084%7CPrice%7Cproxy
Total			$ 5,25	

Rationale as to how this Solution meets one or more of the Challenge's Requirements

i. General Requirements

a. *Significantly reduce the cost of safe, sanitary, and effective toilets. Target cost for a system with all three primary components is US$45 for the total installed cost in the Sub-Saharan Africa market. Solutions somewhat higher than this price range will be considered based on price versus quality. While options may currently exist that meet this price target they are of inadequate quality, durability, and effectiveness and do not meet the minimum requirements of this Challenge*.

The Solver proposes a set of different modules that can be combined according to the local conditions and preferences of the potential users. The basic combination of the said modules that meets the Challenge's minimum requirements plus those contained in the EN 16194 standard, costs US$ 33.28 under the assumed "African archetype" conditions, as detailed in the following summary:

Item	Cost	% of total cost
Basic superstructure	$ 17,14	52%
Squatting pod with tipping box made of steel plate and and urine diverting plastic funnel	$ 7,84	24%
Material cost, 45° trapezoidal section trench , cement-fibre cover , raking required from time to time	$ 3,96	12%
Urine storage (125 l tank 50x50x50 cm, self-built with cement-fibre panels and water-tight mortar + syphon pump to avoid contact with the liquid + jerrycan to spread the urine in the farm, emptying once a week)	$ 4,34	13%
Basic handswashing station ("tippy tap" placed outside of the toilet , usual practice in Africa according to the literature, null cost because made with a recycled PET bottle hanging from a hook or nail).	$ -	0%
TOTAL (basic compliance with EN 16194 and with the Challenge's specifications)	**$ 33,28**	
Saving (-) or excess (+) against target cost 45 US$	**$ -11,72**	

The same combination but with a sitting podium, made with concrete blocks lined with white ceramic tiles on the sitting surface, costs 2 US$ more, with extra 2$S it is possible to install a standard plastic seat toilet (if available, the Solver observed a huge variability of the price of toilet seats):

Item	Cost	% of total cost
Basic superstructure	$ 17,14	52%
Sitting bowl with tipping box and seat made of 20x20 ceramic tiles and and urine diverting plastic funnel	$ 8,69	26%
Material cost, 45° trapezoidal section trench , cement-fibre cover , raking required from time to time	$ 3,96	12%
Urine storage (125 l tank 50x50x50 cm, self-built with cement-fibre panels and water-tight mortar + syphon pump to avoid contact with the liquid + jerrycan to spread the urine in the farm, emptying once a week)	$ 4,34	13%
Basic handswashing station ("tippy tap" placed outside of the toilet , usual practice in Africa according to the literature, null cost because made with a recycled PET bottle hanging from a hook or nail).	$ -	0%
TOTAL (basic compliance with EN 16194 and with the Challenge's specifications)	**$ 34,13**	
Saving (-) or excess (+) against target cost 45 US$	**$ -10,87**	

It is possible to save further 3 US$ if the urine storage is limited to just 1 jerrycan and the urine is distributed daily in the farm, using the technique of subsurface irrigation with buried plastic bottles having some pinholes punched at their bottoms.

In any case, the overall cost of the configuration without accessories provides a good margin of saving compared to the Challenge's 45 US$ goal, and the prices are likely to be applicable to other locations different from the "archetype" Ethiopian context. The Solver observed that some prices varied much from the time when he started drafting the solution (beginning of November) to the end of December, prior to the submission of the solution. For instance, ceramic tiles almost doubled their price in the reference site www.2merkato.com, bricks increased slightly their cost, while some plastic items were discounted. That's why it is important that the Seeker checks the different construction alternatives case by case in the different geographical contexts, since local market conditions may make more convenient the alternatives that were more expensive in the assumed Ethiopian market at the time of checking the costs.

Finally, the savings obtained with the design proposed here allow to include some of the optional features listed below, not required by the Challenge, providing more comfort to the users without exceeding the 45 US$ limit. Please note that some of these options exclude one of the components of the "standard" basic combination. For instance, if the gasification stove is chosen, then the "trapezoidal section trench" is no longer necessary, so the additional cost is 0.40 US$.

Optional functions not required by the Challenge/EU norm but providing more comfort , hygiene and durability	**Additional cost**	**% of basic configuration**
Water tank for rain harvest integrated in roof (approx 70 l)	$ 5,07	15%
Guys and stakes bracing to resist Cat. 1 hurricanes	$ 4,65	14%
Anal washing / shower pan	$ 3,89	12%
Hands washing basin with vanes for toilet items (3 concrete blocks to form the basin and vanes, 1 bottle with foot valve or flexible tube from the roof water tank)	$ 1,26	4%
Gasification stove	$ 3,50	11%
Solar dehydrator (box oven)	$ 7,92	24%
Floor lined with ceramic tiles	$ 9,46	28%
Total, with all optional features (-basic handswashing station)	**$ 35,76**	**107%**

b. *Solutions addressing individual components should show proportional cost reduction for the component. Containment typically represents 40-50%, the interface 20-25%, and the superstructure 30-35% of the total cost of a system*.

Not applicable because the present Solution encompasses all components. It is interesting to note that the cost distribution resulting from the Solution's analysis is in the same order of magnitude of the benchmark defined in the Challenge.

c. *Must be for use by a single family or living group (not meant for communal use/use by the general public).*

The Challenge does not state how many individuals compose the family, so the Solver assumed 6 people. Data on the quantity and composition of the excreta from the cited literature. So, the solution complies with this requisite too.

d. *Component Requirements – any component present in proposed solution should meet corresponding requirements*

i. Containment

- *Must be able to hygienically store or otherwise safely manage waste (so that no humans come in contact with pathogenic waste from the toilet) for the average family for at least one year – approximately 2 cubic meters in volume.*

  The basic solution includes a simple pit for the faeces and litter, 2m^3 volume, and a lid capable of withstanding the weight of a person to keep it dry and avoid contact with people. If necessary, a biofilter can be added, basically for free. The urine is collected separately and left 1 week to mature, according to WHO directives, after that it can be employed directly as fertilizer. The Solver provided some tips for the efficient use of the fertilizer, the minimum area where to spread the urine in order to optimize the crop production and avoid nitrate pollution (based on the EU Directive on Nitrates, max. 300 kg N/ha input to the farm). The solver also included 2 alternatives for the high temperature sanitization of the faeces, which cost a few dollars more than the "passive" containment, but in the case of the gasifier stove allow some savings on the consumption of firewood for cooking and several environmental advantages.

- *Must be:*

- *emptiable by a mechanical vacuum tanker; or*
  N/A

- *removable from the ground such that the waste can be left in the ground to decompose while an alternative place for containment is used and the toilet moved; or*
  The alternative with two “jumbo bags” placed in a pit is meant to comply with this concept. It costs 7 US$ more than the “basic” one, bringing the overall cost nearer to the benchmark limit. It requires less frequent manual labour and extracting the litter with the mature faeces is easier, just lifting the two poles with the full jumbo bag hanging from them (two people necessary). If wooden poles of about 5 cm diameter are available for free, then the cost is comparable to the basic trapezoidal section trench.

- *otherwise facilitate safe management of faecal material*.
  All the alternatives analysed by the Solver address this aspect, in no case the users can come in direct contact with the faeces or the urine. Furthermore, the vault is external to the toilet, in order to avoid the entry of odours. In the opinion of the Solver, the daily removal of the spent litter and its use as fuel in a gasifier stove is the safest option at the lowest cost of all, but the Challenge did not explicitly allow the possibility of reducing the vault’s volume to the minimum, and other uses of the litter different from soil conditioning. For this reason, the Solver proposed this alternative as an optional module.

- *Able to support the weight of anything above it such as people or structures*.

  The pit or trench in the “passive” alternative is covered with cement-fibre panels of adequate thickness, eventually reinforced with woven canes (traditional Italian “*cannucciato*” technique). The only weight these may support is that of a person that may accidentally walk on them, since the vault is external to the superstructure.

ii. *Interface – must be usable or adaptable to be usable by people ranging from young children (as young as 3 years old) to adults, including those with physical disabilities.*

    The Challenge does not specify what degree or type of disability must be addressed. The Solver designed this solution in compliance with the European Standard EN 16194, which encompasses also people with “slight motorial disability”, i.e., not needing a wheelchair to move. The Solver provided two basic interfaces: squatting pod and seat, both of them with a urine diverting funnel, both of them with a “flush” mechanism (required by the said EN standard) to dump the used litter and faeces out of the room. In the case of the squatting podium, the Solver envisaged a simple pair of handle grips made with ropes (or wire) and bamboo or plastic tubes, which are meant to help elderly people or pregnant women to squat. The length of the ropes can be easily extended to allow small children to use the squatting podium too. According to the literature consulted, in rural Africa it is very unlikely to find people with severe motorial disability needing a wheelchair. The most common disability in rural Africa is blindness, which should not be a problem for using either the squatting podium or the seat. Victims of poliomyelitis or of anti-personnel mines having suffered the amputation of a leg may find more suitable the alternative with seat, which costs only 3US$ more than the squatting podium but is still 8US$ cheaper than the 45 US$ limit.

iii. *Superstructure – should allow the user to use the toilet safely (no ability for others to access the toilet while in use), privately (no ability for others to see or hear the user when using the toilet.), and comfortably (no nuisances such as flies or challenges using in a typical range of weather conditions).*

The solution provides a simple lock to keep the door closed, from the inside when in use and from the outside to prevent the entry of animals or pests, or the door slamming in the wind. The walls, floor, roof and door are made of cement-fibre panels plastered with water-tight lime-cement mortar, a gap between the roof and the walls is closed with a fine mesh, in order to allow ventilation and natural lighting but keeping insects out. The high thermal inertia of the fibre-cement panels and the finishing with white lime-cement plaster, eventually painted with lime milk, ensure good bioclimatic compatibility and comfort for the user. It is possible to integrate a 70 l tank in the roof for rain harvesting (drawing not done, only cost estimation).

The solutions would preferably satisfy the additional following criteria (but not essential):

Superstructure

- *Provides sufficient space to perform menstrual hygiene management behaviors and a place for solid waste disposal inside the structure/facility.*

  The size of the superstructure is the minimum defined by the European norm EN 16194 which includes the installation of a minimal washing basin. There's enough room to accommodate a bucket or bin for collecting solid waste and another one for keeping the necessary absorbent litter for the toilet's operation. The suggested positions of these items in shown as dotted lines in Drawing 4.

- *Includes a place for washing hands with soap and water attached/attachable to the outside of the superstructure (integrating a handwashing station where possible—see, for some of many possible examples, SATO Tap or HappyTap).*

  The Solver provided several alternatives of hand washing stations, placed INSIDE of the toilet in compliance with the cited EU norm, and calculated the corresponding costs. It is not clear why the Challenge states that the hands washing basin must be external, anyway there's no problem in installing the washing basin on the external side of the wall. The Solver also developed a simple and cheap alternative to the SATO tap and Happy Tap (plus the Tippy Tap, not mentioned in the Challenge but widely diffused in Africa): a capsized plastic bottle with a homemade foot valve that allows the water to flow when lifting the bolt with the hand's palm. The extra cost of a hands washing basin made with three concrete blocks, providing also some open vanes to keep soap or similar items, is just 1.26 US$.

- *Movable along with the interface to allow for relocation (along with the containment, if it is also movable as described in 4.b.2 above, or to where a subsequent containment option is located)*

  This solution does not need to be moved, because the containment vault is external to it and easy to empty periodically. If necessary, the superstructure can be easily pushed or dragged on the floor for a short distance, or lifted and placed on a cart, because its overall weight is about 100 kg.

- *Ventilated or includes a barrier between the interface and containment to reduce smell.* The containment volume is external to the toilet, the barrier between the interface and containment is a flapping door that opens only during a second when dumping the used litter out, but normally remains closed. A gap between the roof and the walls, closed with mosquito mesh, grants adequate ventilation and daylight while preventing insects to enter. In the unlikely case that smell could escape from the external containment and be carried by the wind, it is easy to place a biofilter between the lid and the faeces containment volume. If the alternative solution proposed by the Solver is considered (containment volume just 12 litres, using the litter as co-fuel in a gasification cook stove every day) the possibility of bad smells is mathematically null because of the very small containment volume and short residence time of the used litter. The collection of urine in closed plastic jerrycans, connected to the toilet via a plastic tube, prevents the smell of urine from diffusing.

- *Materials for interface and superstructure are easily cleanable.*
  If correctly built and plastered, the surfaces are smooth enough and water resistant, they can be cleaned with water, soap and a brush. Painting the walls periodically with lime milk, both inside and outside, ensures a clean aspect and also a good level of hygiene, because the high pH of lime prevents the growth of pathogens. Lining the whole inner surface with ceramic tiles instead of plastering them is certainly possible, but the additional cost exceeds by far the limit imposed by the Challenge: 2100 ETB = 56 US$ for the cheapest tiles (https://con.2merkato.com/prices/material/8/137). An intermediate solution is painting the inner side with synthetic enamel or lack, which is cheaper than the tiles but more expensive than painting with lime milk.

- *Self-installable and self-manageable by the user (or else these are possible at low cost through a service provider)*

  The drawings and instructions provided here are detailed enough for anybody with basic skills and manual tools to build and manage any combination of the proposed modular components in a rural environment of a Developing Country. The Solver concentrated his design efforts on envisaging solutions that require materials available everywhere, like Portland cement, steel wire, timber, screws, etc. The design maximises the use of a rural resource that is usually overlooked: residual crop fibres, in particular long ones like sorghum panicles, coconut coir, straw, reeds, bamboo, corn stalks, etc. Self-management implies using of the urine as a fertilizer and the litter and faeces either as a soil conditioner or as a co-fuel to replace firewood.

Supporting information and drawings

Drawings submitted as unformatted Autocad files. All measures in mm.

Drawing 1: Dimensions of the panels that compose the superstructure

Drawing 2: Assembly of the superstructure

Drawing 3: Detail of the door lock system.

Drawing 4: The squatting pod assembly, including the handholds to support users with reduced mobility (elders, pregnant women) and the "flushing system".

Drawing 5: The tipping box. Construction in the case of using timber planks.

Drawing 6: Sitting bowl and its "flushing system"

Drawing 7: Hands washing basin with a plastic jerrycan

Drawing 8: Hands washing basin with concrete blocks.

Drawing 9: Gasifier stove made with hollow cement blocks

Drawing 10: Containment in a trapezoidal section trench and in Jumbo bags with biofilter

Conclusion

A design that complies with a European standard is likely to be acceptable in a wide range of Countries, or eventually require just minor adaptations. The excel file provided together with the drawings allows the Seeker to easily calculate the cost of any combination of the several modules developed as components of this solution, adapting them to meet any local need. The drawings are detailed enough for anybody with basic skills to build each of the components.

The construction method proposed is nearly carbon-neutral, because the indirect carbon emissions associated to the production of the Portland cement necessary for building the structural panels, are offset by the long-term immobilized carbon contained in the vegetal fibres. Using residual agricultural fibres, like sorghum panicles, coir, etc., and avoiding as much as possible the use of timber, helps preserving the forests. Since Portland cement is a ubiquitous commodity and vegetal fibres are available in any rural zone as a crop waste, the solution can be applied anywhere. Making the panels with the "*cannucciato*" technique or with bulk fibres randomly oriented is just a question of local convenience and preferences, since both production methods yield equivalent rigid and light panels.

The Solver provides the structural calculations for the toilet to resist Category I hurricanes, a frequent problem in many subtropical Countries but overlooked by the Challenge's rules. The additional cost ranges from null (ballast with locally available stones) to 4.65 US$ (steel guys and stakes).

Since most rural inhabitants of Sub-Saharan Africa burn firewood in inefficient open fires or rudimentary stoves (WHO report https://www.who.int/airpollution/publications/fuelforlife.pdf) , the optional gasification stove proposed as "active" treatment method for the faeces and litter opens some development possibilities that were not foreseen in the Challenge's rules:

1) Eliminating -or at least reducing substantially- the hard work of sourcing and transporting firewood that usually burdens women and girls, because the higher efficiency of gasification stoves allows using small quantities of residual biomass as fuel for cooking, instead of big volumes of higher quality hardwood or charcoal;
2) reducing the deforestation caused by sourcing firewood, by replacing all, or at least part of it, with the used litter and residual crops biomass;
3) improving the sanitary safety by processing the faeces at high temperature within 24 hs. of their production;
4) improving the fertility of Sub-Saharan soils -in particular in the dry savanna environment- by the application of the biochar and ashes that remain as residues of the gasification and the urine collected separately.

Since the said alternative for treating the faeces and litter is unconventional and has no references in the literature, in the opinion of the Solver it is worth at least testing it in the field. One possible test protocol could be choosing 3 families as control users, managing any of the "passive" containment systems proposed in this Solution, and three test families that will run their gasification stoves. After several months, compare the quantity of firewood consumed for cooking and the degree of satisfaction of the users.

Final consideration: please note that all the cost analysis was performed on the base of retail prices. Since the final cost is lower than the target defined, this opens the possibility for the creation of small handcraft activities throughout a wide region. If 45 US$ is a cost recognised as affordable within a local community and one individual receives some support (e.g. a microloan) to purchase bulk quantities of material at better prices, and some extra basic tooling (e.g., a concrete mixer and moulds for making the fibre panels in less time), he will then have some modest margin for earning his life as a constructor of standardised toilets based on the design provided here.

Annex 1 - Methods for the production of fibre-cement panels

There are different recipes for preparing cement-wood panels. The simplest one (deduced from the Celenit technical sheet) has a density in the range 500 – 550 kg/m^3 and the following proportions: 600 g wood shavings (or other suitable vegetal fibre), 400 g Portland cement, water in the range 100 – 110 g (calculated theoretically, not stated in the Celenit specifications). Good mechanical properties and a density about 765 kg/m^3 can be obtained with the following mixture proportions (from ref. [xxii]): 330 g wood + 267 g cement + 70 g water + 96 g fine quartz sand.

The quantities indicated hereunder are those necessary for making one single panel with the first recipe. Such a panel is the basic component of the structure: one of the sides, or the door (200 x 100 x 2 cm, total weight 20 – 22 kg) or the floor, (1 equivalent panel, 141 x 141 x 4 cm):

1. Prepare 14 kg of dry vegetal fibres. Suitable fibres are: sorghum panicles, coir fibre, bamboo fibre (from split culms), hemp, esparto grass, rush fibres, chopped straw, sisal, jute, papyrus, fibres of agave leaves (after separating the pulp). The fibres should be 50 to 100 mm long. If using bamboo stripes or wood shavings, they should be cut about 3 mm wide and 0.5 – 1 mm thick.

2. Soak the vegetable fibres in clean water at least overnight.

3. Prepare a carboard mould, 200 cm x 100 cm x 2 cm thickness (inner measures) or two moulds 141x141x2 cm. Recycled cardboard from old boxes is fine. If necessary, join 2 or more carboard sheets with a robust adhesive tape (the type employed for commercial packaging, 50 mm wide). It is not necessary to separate the fibre panel from the mould at the end of the process, since the smooth cardboard surface can be coated with lime, providing an acceptable aesthetical and hygienic finishing for the inner side of the restroom. Alternatively, if the user wishes to employ the same carboard mould several times, then it is advisable to line its inner part with a polyethylene sheet, in order to facilitate the extraction of the finished panel from the mould.

4. Lay the mould on a well levelled ground (possibly in the shadow in order to minimize the water evaporation during the curing period). If the interior of the mould is not lined with polyethylene, then it is advisable to wet the cardboard too.

5. The floor does not necessarily require a mould. Dig a hole in the ground, 141 cm x 141 cm x 4 cm depth. If necessary, level its bottom with some wet sand, and cast the mixture directly in it.

6. Take 7 kg of Portland cement and put it in a big bucket or any adequate container (better if plastic). Add 2.8 - 3 l water to make a fluid mixture (avoid using dirty or untreated river water).

7. Add the wet vegetal fibre, discarding the water where it was soaked (never use this water for making cement: throw it away or use it for irrigation).

8. Mix well until a homogeneous consistency is reached. It is necessary that the cement covers each single fibre, so these can form a random network, sticking to each other.
   N.B.: adding more cement will only increase the weight and cost, without improving the resistance, furthermore worsening the thermal insulation capacity. Please keep as close as possible to one of the two recipes provided here.

9. Pour the fibre–cement mixture into the cardboard mould (or hole in the ground) and level it well, patting the surface with a plastering trowel. The scope is obtaining the most uniform thickness and flattest surface possible.

10. Let the cement harden for at least 2 days (50 % of its final resistance) before attempting removing the panel from the mould. The panels must be kept wet during at least one week by sprinkling water regularly and covering them with plastic sheet or wet newspapers. Avoid direct sun on the panels. This process is called curing of the cement, and improves its final resistance. Do not attempt to employ the panels for construction before 28 days (80% of its final resistance).

11. After 28 days of hardening, the panel is stiff and resistant enough to begin the work.

Alternative method: Only where reeds (nearly 10 mm diameter) are available. Suitable reeds can be, for instance: the common reed (*Arundo donax*), sorghum stalks (*Sorghum bicolor*), Egyptian cane (*Saccharum spontaneum),* elephant grass or Uganda grass *(Pennisetum purpureum).* In Latin America *"totora"* canes *(Schoenoplectus californicus)* and cattail *(Typha latifoglia)* are suitable too. In Asian countries, strips from split bamboo canes are a valid alternative. The method described herein, called "*incannucciato*" or "*cannucciato*" or "*camorcanna*" in Italian, was very common in the construction of the ceilings of the churches, villas and palaces through XVI – XIX Centuries and provides a lightweight and resistant panel, with excellent thermal properties. There are two basic techniques:

a) Reeds are cut to the required length, disposed parallel to each other in a single layer until reaching the desired width, and woven with thin steel or copper wire, or fibre strings (photo A). The resulting mat is then plastered with stucco, gypsum, light mortar or Portland cement. For the purpose of this challenge, it is advisable to add a second mat with the canes perpendicular to the first one, binding both mats with steel wire before plastering the resulting panel on both sides. This will provide more rigidity, yet yielding a lightweight panel with good thermal insulation properties.

Photo A. Single-layer traditional ceiling made with "incannucciato" plastered with gypsum. Source: https://www.infobuild.it/norme-tecniche/consolidamento-di-solai-in-legno/

b) Split and flattened reeds are interwoven, and the resulting mat is then plastered (figure B). Like in the former case, stacking mats with layers of cement allows obtaining the desired thickness.

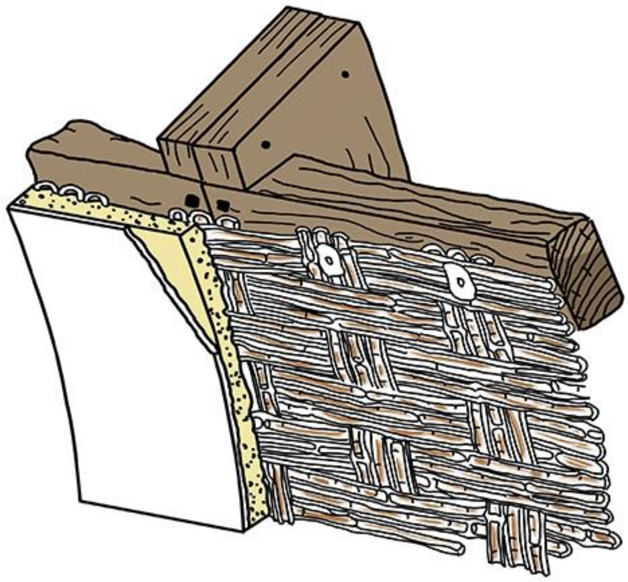


Figure B: Scheme of a “false vault” made with interwoven split canes, typical of most churches built in Italy (source: https://www.kimia.it/it/blog/come-si-rinforzano-volte-in-camorcanna)

Suitable plasters for the *cannucciato* are: pure Portland cement, mortar of cement and sand (1 part cement, 3 parts sand), mortar of cement, lime and sand (1 part cement, 1 part spent lime, 5 parts of sand). The mortar of sand and spent lime (3 parts of sand and 1 of lime) provides a shorter curing time and lime is slightly cheaper that Portland cement, but this mixture has lower mechanical resistance than pure cement or cement mortar. If employing pure Portland cement, the reed mats must be soaked in water, in order to provide the necessary moisture during the cement’s curing process.

Choosing between the fibre-cement or the *cannucciato* option is just a question of local convenience. The *cannucciato* requires no mould, and reeds or bamboo mats are a very cheap and widely available commodity in many Countries (especially in Asia). Whatever the method and material chosen, it is necessary to produce five panels as described above (3 side walls + the door; one floor panel 141 x 141 x 4 cm) and one roof panel 141 x 141 x 2 cm, that requires half of the fibres and cement quantity specified. The roof panel can be replaced with a metal sheet or with thatching, or textiles, or woven bamboo or reeds mats without plastering, because it has no structural function. The back wall must have a rectangular hole, necessary for the “flushing system” (see the corresponding section). The hole can be cut from the finished panel using a fine-teeth saw, or produced directly during the moulding process, by placing an adequate insert in the mould (for instance, a plank of plywood, or wood, or a stack of carboard rectangles, with overall thickness greater than 20 mm).

N.B.: Although reference [xxiii] shows evidence that good panels could be produced with long vegetable fibres (30 – 60 mm, soaked in water at least 6 hs.) and watertight mortars of Portland-lime-sand, the Solver found no evidence of commercial panels made with such a mortar. Since the compression resistance of pure Portland cement is 30 – 40 MPa and that of type S mortar is 10.3 MPa (ref. [xviii] below), the Solver chose the well-proven Celerit™ panel composition for the cost calculations, but this is an aspect that merits some research on the field, since mortar-fibre boards could be slightly cheaper.

Waterproof mortar

Panels that can be subject to permanent contact with moisture -like the floor, the squatting slab, an eventual urinal and the hands washing basin- must be plastered with a water-tight mortar, both for preserving their structural strength and for providing a smooth and hygienic surface. The following recipe (Type S lime mortar as per ASTM C 270, extracted from ref. [xxiv]) should be enough for plastering 1 m^2 of panel: 2000 cm^3 of Portland cement, 660 cm^3 of hydrated lime (in powder), 7000 cm^3 of fine sand (dry), 1800 cm^3 of water.

The walls, door and roof do not need the waterproof plastering. They can be finished with a cheaper lime-sand mortar (1 part of quicklime and 3 parts of fine sand) or lime-cement mortar (3 parts of lime and 1 part of cement) in order to provide a smooth and tidy aspect, but this is not mandatory for structural purposes. Painting the walls and roof with lime milk will reflect the sunlight, keeping the interior of the toilet fresher. Lime provides some antibacterial effect too. Painting the superstructure with limewater (milk of lime) from time to time will ensure a longer life of the superstructure.

Based on the former considerations and for the purpose of cost analysis within this Challenge, the Solver assumed employing pure Portland cement as the binding agent, like in the Italian commercial product Celerit™. The finishing of the floor is made with waterproof mortar of quicklime cement and sand, with the recipe explained above. The walls and door are assumed to be just painted with limewash (1 kg of quicklime + 1.7 – 2 litres of clean water for the interior and exterior of the superstructure).

Annex 2 - Analysis of the stability in high winds

In the worst case, the wind is pushing on the structure from the backside. The aerodynamic forces are the lift (F_l) and drag (F_d) generated by an inclined square plate (assumed 10° maximum angle of attack, either because intentionally built with a sloping roof or because of an accidental deformation), and the drag on a parallelepiped body (F). The only stabilizing force is the weight of the structure (assumed empty and the walls not plastered). The centre of rotation of the capsizing and stabilizing moments is the point O (figure 1).

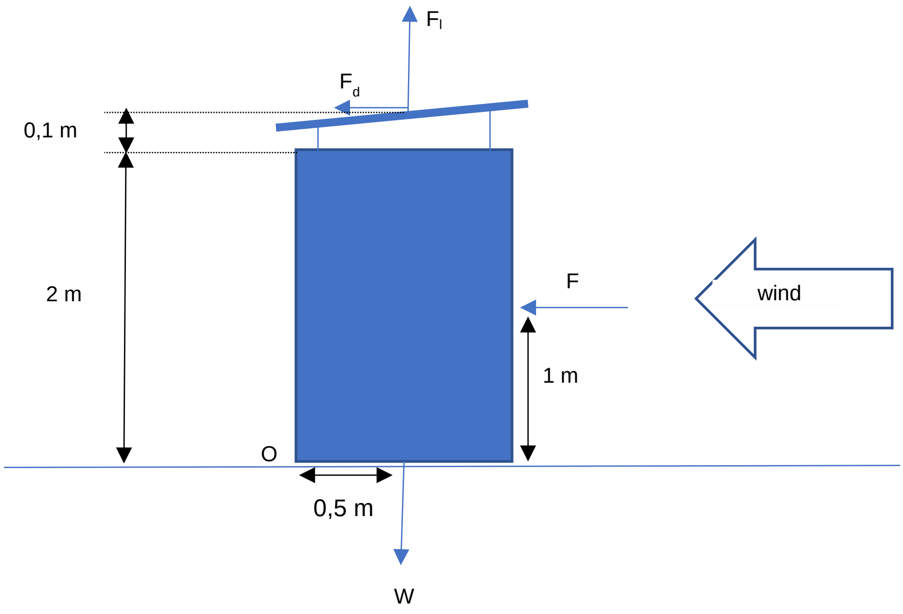


Figure 1: static scheme of the forces acting on the structure in the worst case.

At the limit equilibrium point, the sum of the capsizing (positive) and stabilizing (negative) moments is 0.

$$0 = F \times 1 + F_d \times 2{,}1 + F_l \times 0.5 - W \times 0.5$$

The values of the forces are:

W = 9.8 m/s^2 (10 m^2 x 10 kg/m^2) = 980 N

The general expression of an aerodynamic force is:

$F = 0.5\, \rho\, C\, A\, V^2$

Where ρ is the density of the air (1,20 kg/m^3), A is the area of the element (m^2), C is a non-dimensional coefficient (lift or drag) and V is the wind speed (m/s). In our case:

F = 0.5 x 1.20 x 2.05 x 2 x V^2 = 2.46 V^2

F_l = 0.5 x 1.20 x 0.35 x 1 x V^2 = 0.21 V^2

F_d = 0.5 x 1.20 x 0.15 x 1 x V^2 = 0.09 V^2

Note: C_l = 0.35 and C_d=0.15 correspond to a flat square plate in a free stream. Data from ([xxv]).

Replacing in the equilibrium formula:

$0 = (2.46+0.21+0.09)\ V^2 - 980 \times 0.5$

$V = 13.4$ m/s (48 km/h)

In the assumed place (Adama, Oromia Region, Ethiopia), the average wind speed at 10 m height ranges from 2.5 to 4.5 m/s (fig. 2), which means that the occurrence of a 13.4 m/s wind at 2 m height is very improbable, so the structure's own weight is enough to ensure that it will not be blown away under the local storm conditions. The speed of monsoon-like winds is in the range 4 to 6 m/s ([xxvi]).

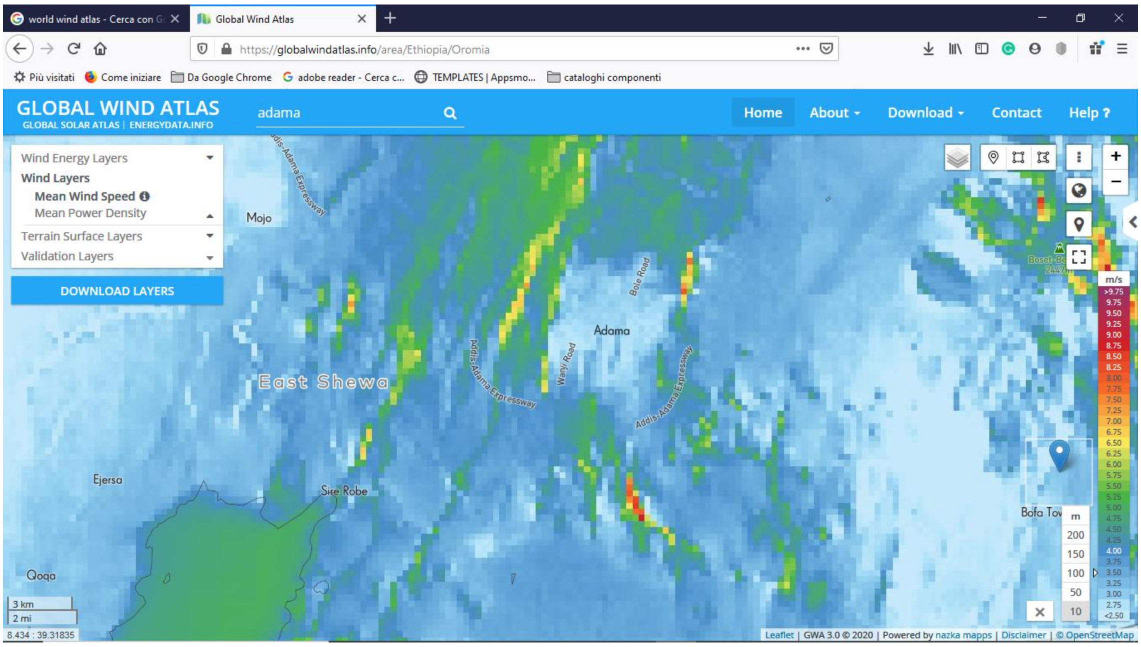


Figure 2: Average wind speed in the Adama area. Source Global Wind Atlas

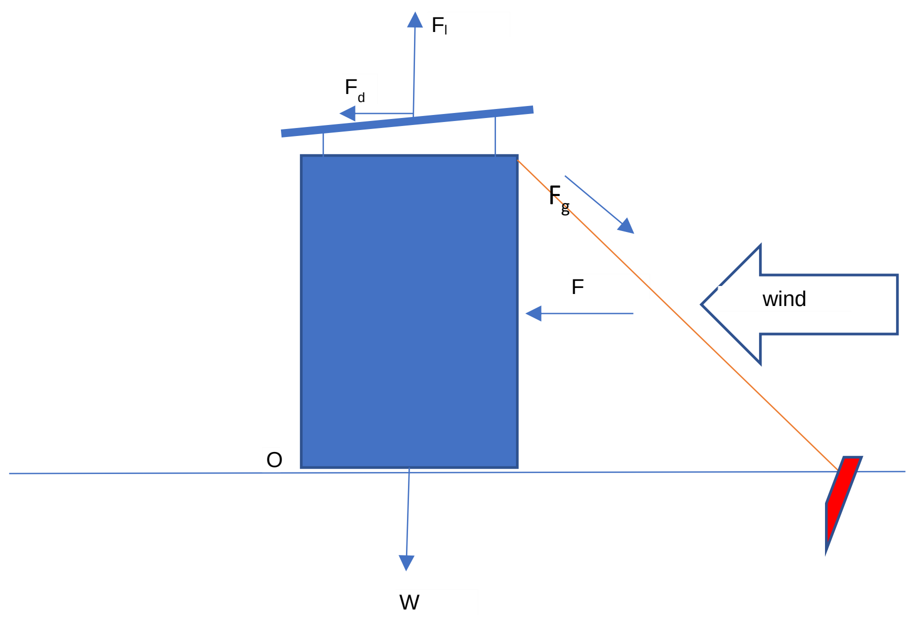
In places where typhoons or similar events are likely to happen, it is necessary to anchor the structure with guys, or ballast it with stones or sand bags. Ballasting with stones or sand bags will require no cost (assuming the said materials are collected in the neighbourhood) but more manual labour to carry and secure the ballast to the structure. Covering the walls with a layer of sand bags or stones, secured with a steel wire mesh, has a bioclimatic advantage: it will increase the thermal inertia of the construction, making it cooler during the day and warmer during the night. In places subject to frequent hurricanes, it may be a good idea doubling the thickness of the panels and using longer screws, in order to ensure the durability of the structure. This will double the strength but will not double the construction cost, since the vegetal fibres are assumed to be free and the Portland cement represents ¼ of the grand total (see cost analysis in the next section).

In the case that the structure must be erected in a place subject to the risk of a Class I hurricane (119 km/h = 33 m/s, according to the Saffir-Simpson scale https://www.nhc.noaa.gov/aboutsshws.php), then the quantity of ballast (B) can be calculated easily, as follows:

$0 = (2.46+0.21+0.09)\ 33^2 - (980+B) \times 0.5$

$B = 3005.64 \times 2 - 980 = 5031.28$ N = 513.4 kg (roughly 14 bags of 25 l capacity filled with dry sand or gravel)

If securing the structure with guy ropes is preferred to ballasting, then the static scheme is the one shown in figure 3.



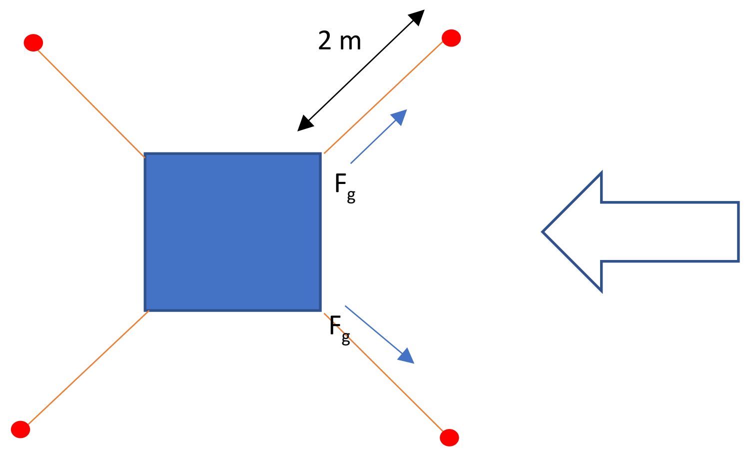


Figure 3: Forces on the superstructure braced with guy ropes.

The forces F_g can be projected on their x, y and z axis:

Fg_z = Fg sen 45° = 0.707 Fg

$Fg_x = Fg_y = Fg_z$ sen 45°= Fg sen^2 45° = 0.5 Fg

The equilibrium equation is then:

0 = (2.46+0.21+0.09) 33^2 – (2 Fg_z x 0.5 + 2 Fg_x x 2)

3005.64 = 0.707 Fg + 2 Fg

Fg = 1,110.32 N

The guys can be made with standard galvanized wire of 2.5 mm diameter, a gauge available everywhere. The mechanical properties are those reported by one of the many manufacturers (https://mildsteelmesh.com/mild-steel-mesh/hot-dipped-steel-wire.html). One single wire can withstand 6,872 N (collapse limit) or 1,472 N (permanent load).

Annex 3 – Hands washing

A very cheap alternative to the tippy tap and the jerrycan with faucet is buying an intravenous kit (photo I) in the nearest town or city pharmacy, and cutting the needle off. In practice, the dosing end must be plugged into the bottom of a plastic bottle or jerrycan, the opposite end with the needle and the excess of tube must be cut off, so the tube clamp can be employed for opening and closing the tube, like a tap.

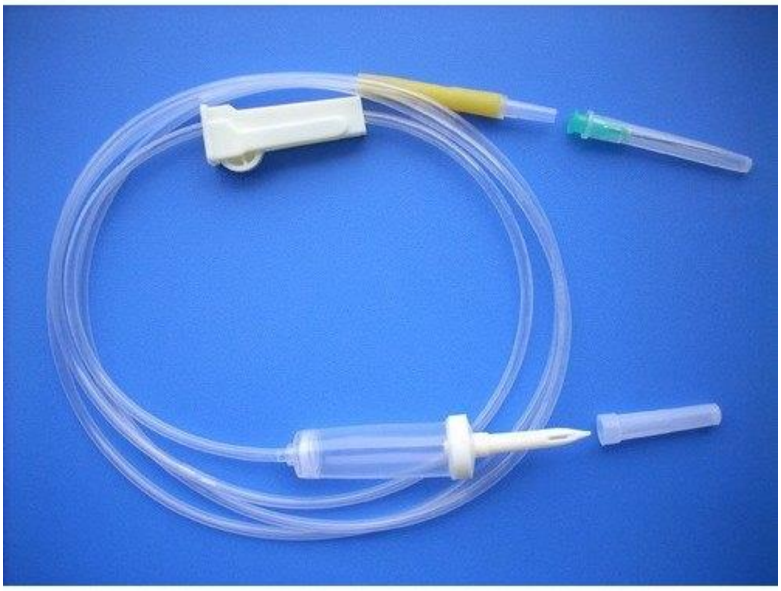


Photo I: An intravenous infusion kit or IV (price in India from 0.1 to 0.16 US$, source https://www.indiamart.com/proddetail/romsons-disposable-infusion-set-22054115230.html).

Recovering the water after washing the hands may be important for its reuse in agriculture. A washing basin is then necessary. A 20 cm diameter funnel with a plastic tube inserted in its spout costs about 1.44 US$ but is not nice to see. The Solver took as model the dimensions of a commercial washing basin for reduced spaces (Flaminia™), similar to the ones installed in the commercial WCs shown in photos 1 and 2. The external measures of the Flaminia™ washing basin are 350x230x120 mm, the net inner space for washing the hands is 310x150x75 mm, figure II.

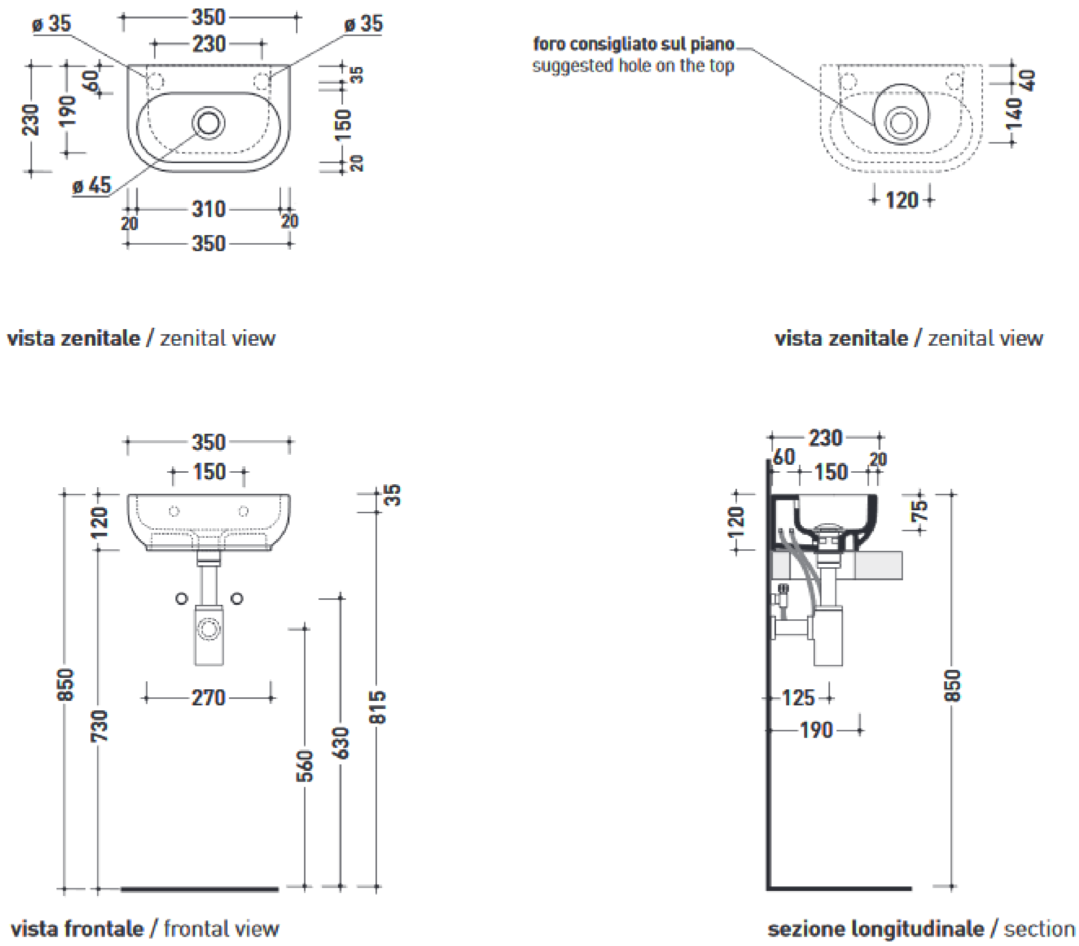


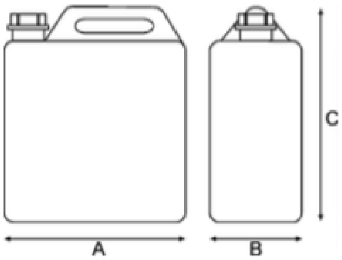
Figure II: The measures of the minimalist hand washing basin by Flaminia were assumed as model for the proposed design (source: https://www.aisilbagno.it/wp-content/plugins/ant-webcommerce/global/files/PS23LM_pdf_it.pdf)

There are several ways of making a small washing basin with dimensions similar to the Flaminia ™ model, where the tap can be replaced by an intravenous kit connected to any suitable water container placed over the basin:

i. Asking a local potter to make a shallow pot with the desired size and shape, or adapting an already existing bowl with diameter about 200-250 mm and depth 100-120 mm. In the special case of Ethiopia, traditional pottery is cheaper than industrial goods and the price of a bowl or jar could be as low as 0,30 US$ ([xxvii]). The option in this case is just installing a shelf on one of the side walls, using a wooden plank (200 x 300-400 mm) and two steel brackets. The overall cost of a jar for keeping water (nearly 5 l), a bowl, a small dish for placing the soap, and the wooden shelf with two steel brackets fastened with screws is about 1.10 US$ (the wooden plank and the paint are already inputted to the construction of the tipping box, so they are assumed as free for the construction of the shelf). Nevertheless, local pottery may not be available or affordable everywhere so this alternative is not “universal”.

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
Local pottery (estimated average price per piece)	3	5	$ 0,41	https://core.ac.uk/download/pdf/39299702.pdf
Timber shelf 2.5cmX20cmX40cm - Ethiopian (Shashemene)	1	0	$ -	the full cost from https://con.2merkato.com/prices/material/5/357 was already inputted to the tipping box construction, the shelf is a scrap of the same
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,03	100	$ 0,08	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanised steel brackets for wood	2		$ 0,60	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
Super synthetic enamel	1	0	$ -	https://con.2merkato.com/prices/material/10/896 . The cost was already inputted to the construction of the tipping box
Total Material Cost, clay bowl and jar placed on wooden shelf			**$ 1,09**	

ii. Washing basin made with a 5 l plastic jerrycan. Observe that the measures of this item (figure 6) are similar to those of the Flaminia washing basin.



Capacity lt.	A (±5) mm.	B (±5) mm.	C (±5) mm.
5	270	140	250
10	310	190	280
20	350	190	380

Figure III: Measures of standard plastic jerrycans. Source: https://maestrisrl.com/it/taniche-omologate-in-metallo-2/

The cost may vary from null (used jerrycan) to 0.65 US$ (price in Uganda https://www.jumia.ug/nice-jerrycan-5-litres-white-2462775.html, because the Solver could not find any information on the cost in Ethiopia, change 1 UGX = 0.00027 US$, retrieved from Google Finance on 01/11/2020). The solution proposed here requires at least one jerrycan as the washing basin and one plastic bottle (assumed to be free) or two jerrycans if more water capacity is desired. The manufacture process and the installation on one of the lateral walls is shown in drawing 7. The total cost in the worst case (purchase of 1 jerrycan + 2 IV kits) is 0.82 US$. It is possible to replace the bottle and the IV kit with an adequate jerrycan with tap, if available in the market at an affordable price. The Solver found a large variability of the prices of jerricans with tap, all of them much more expensive (<10 US$) than the option of plugging an IV kit into a standard jerrycan or plastic bottle, so this alternative must be checked case by case.

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
5 litres plastic jerrycan	1		$ 0,65	Price in Uganda https://www.jumia.ug/nice-jerrycan-5-litres-white-2462775.html
Intra venous infusion kit inserted into a hole in the jerrycan	2		$ 0,09	Price in India 7 - 12 INR = 0,09 - 0,16 US$ https://www.indiamart.com/proddetail/iv-infusion-set-16876255912.html
Plastic bottle	1			assumed as free, recycled bottle
Galvanised steel screws for wood , 40 mm, M4.8 (kg)	0,03	100	$ 0,08	Price in Ethiopia not available, assumed the same price per kg as nails https://con.2merkato.com/prices/material/6/102
Galvanised steel brackets for wood			$ -	Price in Ethiopia not available, assumed 0.3 US$ extrapolating from here: https://www.alibaba.com/product-detail/metal-stamping-kit-steel-reinforced-corner_62002724778.html?spm=a2700.details.deiletai6.5.6f464e37EdWgVM
Total Material Cost, 2 plastic jerrycans			**$ 0,82**	

iii. Washing basin made of watertight mortar, eventually painted with white synthetic enamel. The cost of this solution would be virtually null, because the cost of one sack of cement and the synthetic enamel has already been inputted entirely to the construction of the superstructure and the tipping box, so it is possible to employ the leftover material for making the washing basin. Nevertheless, shaping a washing basin with an agreeable design, similar to the Flaminia ™, requires some skill for preparing an adequate mould, for instance, with clay or gypsum. The Solver assumed that most of the potential users of this Solution are unskilled, hence he did not develop this option further.

iv. If the look is not an issue, then a simple solution requiring no skill at all is to make the washing basin with two or three standard concrete blocks like the ones employed for the squatting pod (standard external measures 400 x 200 x 200 mm, thickness of the walls 20 mm, weight 20 – 25 kg). Observe that removing the central wall of the block leaves an inner space of 160 x 360 x 200 mm, which is slightly bigger than the Flaminia ™ washing basin assumed as a model. It is relatively easy to plaster the corners with mortar, in order to round them. The design of this solution may look a bit crude, but it is fully functional (Drawing 8). Finishing the surface with fine cement plaster and painting it with synthetic enamel will provide a smooth and clean aspect. The lower block can be employed as a container for keeping the soap, a roll of paper towel, water bottles or any other similar items. The water for washing the hands can be kept in a bottle suspended on the washing basin, like in the tippy tap design, or in any other suitable container. A hole on the back panel will provide adequate water drainage. The used water can be collected in a bucket placed outside of the superstructure, in order to water the vegetables in the yard, or re-used for the laundry. The total cost ranges from a minimum of 0.86 US$ (only two blocks, secured to the wall by means of steel wire + tippy tap-style water supply) to a maximum of 1,26 US$ (3 blocks stacked as a column wash basin, cemented to the floor and wall with Portland cement + IV kit + one 5-litre jerrycan hanging from a hook on the wall).

Material	Qty. Required	Local Unit Cost (ETB)	Cost (US$)	Source and remarks
5 litres plastic jerrycan	1		$ 0,65	Price in Uganda https://www.jumia.ug/nice-jerrycan-5-litres-white-2462775.html
Intra venous infusion kit inserted into a hole in the jerrycan	1		$ 0,09	Price in India 7 INR = 0,09 US$ https://www.indiamart.com/proddetail/iv-infusion-set-16876255912.html
concrete block	3	15,6	$ 1,26	standard sizes concrete blocks https://www.unikblockmachines.com/info/what-standard-sizes-of-hollow-concrete-block-21025537.html ; Price from https://con.2merkato.com/prices/material/4/59
synthetic enamel and Portland cement	as needed		$ -	null, because already inputted to the construction of the tipping box
Total Material Cost, concrete blocks + jerrycan + syphon pump			**$ 1,26**	

Annex 4 – Gasifier stove, thermal recovery and use of the biochar as litter additive and/or soil conditioner

3) The basic theory of gasifier stoves can be found in the following sites: https://energypedia.info/wiki/Improved_Cookstoves_and_Energy_Saving_Cooking_Equipment and https://energypedia.info/wiki/Gasifier_Stoves. A few of the many examples of DIY pyrolytic (gasifier) stoves in the internet can be found in the following links:

   a. theory and practice: https://www.youtube.com/watch?v=SaeanoWZE7E,

   b. DIY with cans https://youtu.be/dM47gtKpGYY , https://youtu.be/KRsFO-5TlrM ,

   c. trial and error optimization: https://youtu.be/WgoW70yzhw4.

   The operation of such stoves is essentially odourless and smokeless. The ideal fuel is residual biomass of small grain size, for instance cereal husks, chopped reed, chopped straw, fine wooden sticks, sawdust, etc. The gasification leaves variable amounts of residual biochar. There are three ways the biochar can be employed in a rural socio-economic context like the one supposed for this Challenge:

   - Soil conditioner. There is a vast number of studies in the literature about the increase in fertility thanks to biochar added to the soil: higher water retention capacity, higher efficiency in nutrients uptake from the plant's roots, prevention of the erosion, carbon sink. A summary is provided in ref. [xxviii] , cited here as an example of the many papers available. The application rate of biochar on arid soils is in the range 0.5 to 20 ton/acre (124 g/m^2 to 4.9 kg/m^2). This means that a family like the one assumed as model for this challenge can apply the minimum fertilization rate to 77 m^2 every week, i.e. roughly one acre/year can be recovered from desertification.

   - Briquettes. The process is explained in detail in a FAO manual (ref. [xxix]). In the context of this Challenge, the said option seems difficult to implement.

   - Using the biochar as absorbent litter material for the toilet. Because of its capacity to absorb moisture and odorous compounds, this option seems very easy and straightforward to implement in the context of the Challenge. Using biochar as absorbent litter for the toilet (or at least as an additive to the available litter) will increase the safety and comfort of the proposed solution.

   Assuming that the litter is a mixture of 12 litres (600 g) of chopped straw or cereal husks and 2,4 kg of fresh faeces, with an overall moisture of 42 %, its thermal energy content can be estimated as the LHV (lower heating value) of the vegetal matter, multiplied by the percentage of dry matter i.e.:

   E_{th} = 58% x 14 MJ/kg x 0,6 kg = 4.87 MJ

   Note that 14 MJ/kg is a pessimistic estimation (rice husks or similar biomass with high ash content, ref.[xxx]). Sawdust or wood shavings can have a LHV of about 18 MJ/kg.

   A simple natural draft gasifier stove has an efficiency of 22 – 25% (ref. [xxxi]). Let's assume a cautious 20% efficiency and that cooking for 6 people requires the equivalent energy of boiling 10 litres water (twice the usual benchmark for cook stoves), i.e.

   $Net_{th\ demand}$ = 10 kg x 4.18 KJ/kg K x 100 K = 4.18 MJ.

The stove must then have enough capacity to accommodate a quantity of fuel able to generate a gross thermal output equal to 4.18 MJ/0,2 = 20.9 MJ. The necessary quantity of wood shavings or any other low-value biomass is then:

Woody biomass = (20.9 – 4.87) MJ / 18 MJ/kg = **0.9 kg** ⇔ **6 dm^3** (wood chips, sawdust or wood shavings, coconut shells, density 150 g/ dm^3)

Or

scrap biomass = (20.9 – 4.87) MJ / 14 MJ/kg = **1,14 kg** ⇔ **7.6 dm^3** (chopped and pressed straw, cereal husks, chopped reeds or canes, bark, density 150 g/ dm^3)

The inner pyrolysis chamber must then have 18 – 20 litres capacity in order to accommodate both the litter and the biomass fuel. Let's assume arbitrarily 20 litres inner volume, and a section 20 x 20 cm (assuming the construction with hollow concrete blocks and to easily accommodate a pot on top of it), then the minimum chamber's length will be 50 cm. Drawing 10 shows the basic construction using 12 hollow concrete blocks. Of course, it is also possible to build it with clay, stones, bricks or even cement/sand mortar. For the purpose of the Challenge, the cost estimation corresponds to the solution based on concrete blocks, the construction sketch is included in Drawing 10. The operation sequence is very simple:

i. Dump the litter into the gasification chamber;

ii. Fill it up with wood shavings or chips, chopped reeds or canes, cereal husks or any other similar biomass;

iii. Light the top and wait a few minutes until it begins to burn;

iv. Place the pot on top and adjust the flame intensity by opening or closing the air intakes at the base (for instance by placing stones or wood plugs in some of them). The ideal flame regulation should produce little or no smoke, the ideal flame will be blueish (maximum fuel efficiency).

v. Once finished cooking, take out the loose block at the base and recover the ash and charcoal with a rake or fire iron.

Annex 5 – Dimensioning the solar box

Based on the assumption n), separation of urine, the quantity of water to evaporate is only the moisture of the faeces + 10% to account for some residual moisture of the litter material:

M = 6 people x 0.5 kg faeces x 50% x 1.10 = 1.65 kg/day

The energy to evaporate that quantity of water is:

E = 1.65 kg [4.2 kJ/kg°C (100°C - 36°C) + 2,260 kJ/kg] = 4.172 kJ = 1.16 kWh

The average solar irradiation on a horizontal plane at the "archetype" sub- Saharan area chosen for this example is in the range 2,200-2,300 kWh/m^2.year = 6 – 6.3 kWh/m^2.day. The data were taken from the Global Solar Atlas: https://globalsolaratlas.info/map?c=11.609193,8.4375,3, figure A.

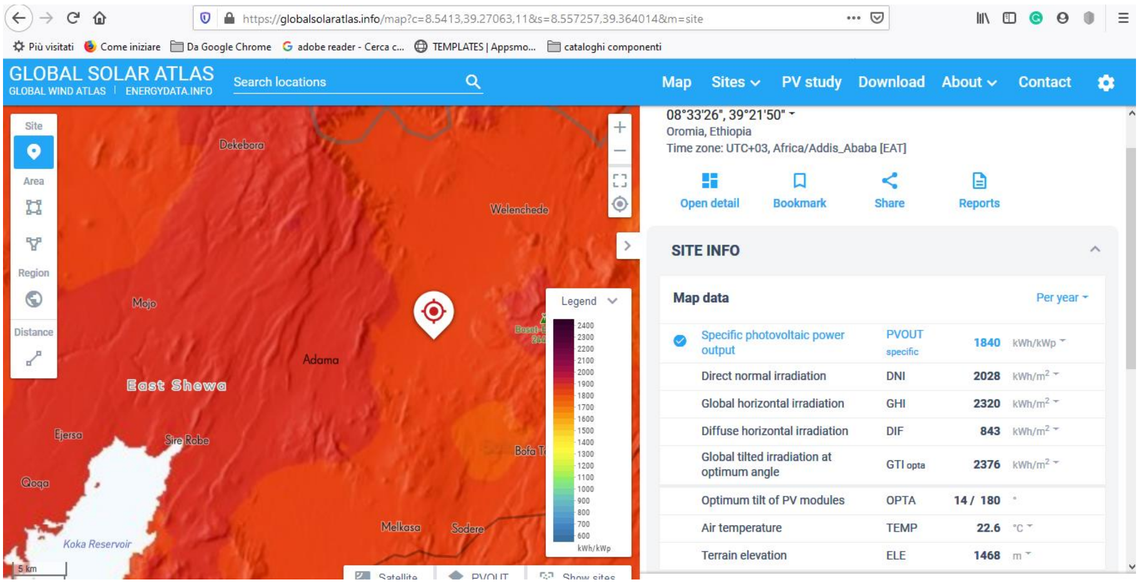


Figure A. Solar irradiation in the area of Adama, Ethiopia

In order to calculate the solar collection area, A [m^2], necessary for capturing at least 1.16 kWh in one day at the given locality, it is necessary to estimate the efficiency of the solar collector by means of a simple energy balance. Assuming that the litter is processed daily, the inner containment volume will be a metal cylinder, 30 cm diameter x 20 cm height. The same will be placed inside a box having inner measures 50 x 50 x 50 cm. The inner chamber will be lined with kitchen aluminium foil. The walls and bottom of the box are assumed as 20 cm thick. Essentially, the box is made with two cardboard boxes, filled with straw as insulant material. The external box is then at least 90 x 90 x 70 cm, the inner box is 50x50x50 cm. The top is a window glass pane, 50 x 50 cm, minimum thickness 3.5 mm. The required sunlight collection area, *A*, will be the base of a trunk pyramid. The optical concentration factor is then, by definition, the ratio of A to the glass window's area (0.25 m^2). Figure B shows the sketch.

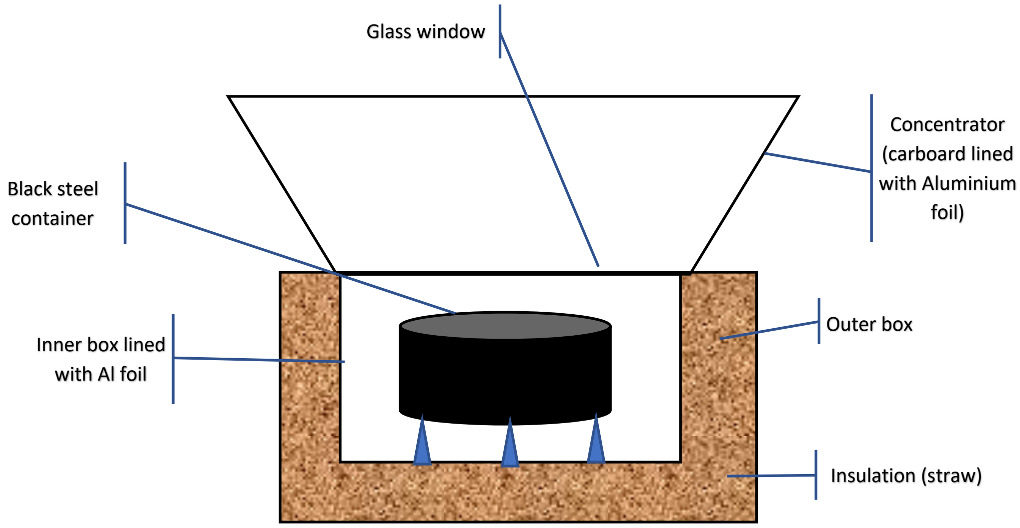


Figure B: Sketch of the solar box (section)

The energy input absorbed by the black container inside the box is:

E_{in} = G x (1-a_r) x A x T x a

Where G is the total incident radiation (assumed 6 kWh/m^2.day in this example), (1-a_r) is the fraction of the same reflected by the concentrator to the glass (70%), T is the transmittance of the glass (85% in case of single pane glass ref. [xxxii]), and a_w is the average absorptance coefficient of the black steel container (90%, taken from https://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html, assuming that the walls will be blackened with char or smoke). The unknow factor is A, the collection area of the concentrator.

E_{in} = 6 x 0.7 x 0.85 x 0.9 x A = 3.21 kWh/m^2.day x A

Assuming that the desired (average) inner temperature at equilibrium is 80°C during 8 hours a day, that the average outer temperature is 20°C (pessimistic, since in most Sub Saharan environments t>25 °C), the thermal losses are:

E_{out} = E_v + (U_g A_g + U_w A_w) (80°C – 20°C) x 8 hs/day

Where:

E_v = energy lost as evaporation of the waste's moisture = 1.16 kWh/day

U_g = overall thermal losses coefficient of the glass pane (mostly convection and radiation) = 7.9 W/m^2°C (from https://www.engineeringtoolbox.com/heat-loss-transmission-d_748.html)

A_g = area of the glass window (0.25 m^2)

U_w = overall thermal losses coefficient of the bottom and side walls (mostly conduction) = 0.45 W/m^2 °C (0.09 W/mK / 0.2 m = 0.45 W/m^2 K, data from https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html).

A_w = area of the bottom and side walls of the box (4x0.7x0.9 + 0.9x0.9) = 3.33 m^2

E_{out} = 1.16 + (7.9 x 0.25 + 0.45 x 3.33)/1000 x 60°C x 8 hs = 2.83 kWh/day

In equilibrium

$E_{out} = E_{in}$ → 2.83 kWh/day = 3.21 kWh/m^2.day x A → A = 0.88 m^2

N.B. In the range of latitudes from the Equator to 30°, the average solar radiation on a horizontal plane does not vary so much. For instance, the average daily irradiation in on a horizontal plane in Johannesburg, -33° latitude, is 2057 kWh/year m^2, i.e. 5.63 kWh/day.m^2. Hence, a window of 1.2 – 1.5 m^2 will be more than enough in most Sub-Saharan locations. For our purposes, the concentrator will be a trunk of pyramid, 1 m x 1 m upper base, 0,5 x 0,5 m lower base, 50 cm height. It can be made with cardboard lined with aluminium foil. The optimum orientation is with the area A facing straight to the S in the N hemisphere, or to N in the southern hemisphere, and the whole system must be tilted by the latitude of the place (8° in the case of the example location), figure 9.

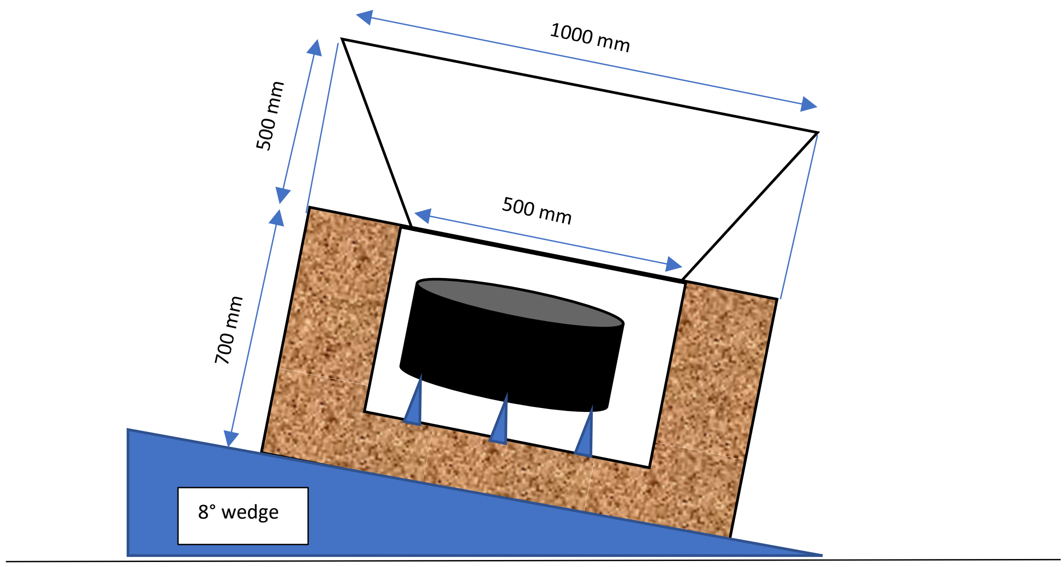


Figure C: the size and optimum installation of the solar box in Adama, Ethiopia.

Since it is possible to employ recycled carton to make the box and the insulant is straw, bark chips or any similar other loose material (e.g. paper balls made with old newspapers), the only materials to purchase are the glass window, the aluminium foil and the steel sheet to build the container (a strip 990 mm x 300 mm to form the wall of the cylinder, two plates 350 x 350 mm to form the bottom and cover. The elements can be assembled by punching some holes and sewing them together with steel wire, size of the sheet is roughly 1 m x 70 cm).

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