

## Research Paper

# Understanding the costs of urban sanitation: towards a standard costing model

Tristano Sainati, Fiona Zakaria, Giorgio Locatelli, P. Andrew Sleigh and Barbara Evans 

### ABSTRACT

There is a dearth of reliable cost data for urban sanitation. In the absence of high-quality global data, the full cost of sustainable implementation of urban sanitation remains uncertain. This paper proposes an approach for developing bespoke parametric cost estimation models for easy and reliable estimation of the costs of alternative sanitation technologies in a range of geographical contexts. A key requirement for the development of these models is the establishment of a large database of empirical information on the current costs of sanitation systems. Such a database does not currently exist. Two foundational tools are proposed. Firstly, a standard metric for reporting the costs of urban sanitation systems, total annualised cost per household. Secondly, a standardised approach to the collection of empirical cost data, the Novel Ball-Park Reporting Approach (NBPRA). Data from the NBPRA are presented for 87 individual sanitation components from 25 cities in 10 countries. Broad cost ranges for different archetypal systems have been estimated; these currently have high levels of uncertainty. Further work is proposed to collect additional data, build up the global database, and develop parametric cost estimation models with higher reliability.

**Key words** | benchmarking, cost estimation, costing standards, urban sanitation

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### HIGHLIGHTS

- A bespoke parametric cost estimation approach is proposed for reliable estimation of urban sanitation costs.
- A standard metric for reporting the costs of urban sanitation systems; total annualised cost per household (TACH) is presented.
- Broad cost ranges for different archetypal systems have been estimated, based on 87 individual sanitation components from 25 cities in 10 countries.

### INTRODUCTION

More than 1 million people per day must gain and maintain access to safely managed sanitation to meet the sanitation

target of the sustainable development goals (Mara & Evans 2018). A significant majority of this 'new' sanitation investment will be made in urban or urbanising areas. While standalone household and community sanitation services will continue to be important in rural areas (in both rich and poor countries) in denser urban areas, toilets that

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provide sanitation at home must be planned and operated as part of a professionalised service – which transports excreta either through pipes or road-based networks for management away from the home.

A key challenge for SDG 6.2 arises from the dearth of reliable and comparable benchmark estimates of the unit costs of these ‘networked’ services (Daudey 2017). Compared to other infrastructure services, costing in sanitation is characterised by ambiguity concerning both terminology and costing standards. Other sectors tend to employ familiar, readily understood, summary indicators for the global comparison of costs (Merrow 2011; Ansar *et al.* 2014; Locatelli *et al.* 2017). For example, the concept of the cost per kilowatt-hour (kWh) of energy is well established (De Roo & Parsons 2011; Geissmann & Ponta 2017; Lai & McCulloch 2017) and its utility in comparing the costs of services can be easily understood even by a layperson. By contrast, there is no agreed metric for comparison of the costs of sanitation delivery (Daudey 2017).

This paper reports early findings from the Cost and Climate for Urban Sanitation (CACTUS) project which aims to fill some of this gap. We introduce a proposed standard cost metric for urban sanitation, Total Annualised Cost per Household (TACH) and per Capita (TACC), and propose a strategy for developing a parametric method that would enable the estimation of TACH/TACC for new sanitation systems around the world. We also describe a Novel Ball-Park Reporting Approach (NPBRA) which is aiding in the establishment of a global database of empirical benchmark costs as a basis for this future parametric cost estimation tool. Indicative early results from the global database of NPBRA data are presented.

## THE CHALLENGE OF COSTING IN URBAN SANITATION

In a recent systematic review, Daudey (2017) observes a dearth of reliable studies reporting clearly on the full costs associated with the delivery of sanitation services worldwide. While there has been notable and important work done on estimating benefit–cost ratios in sanitation, see for example, Whittington *et al.* (2012), Hutton 2013 & Cronin *et al.* (2014), these rely on a very small number of empirical

data and limited modelling to derive the cost estimates on which they are based.

One approach to estimating the cost of services is to use the price as a proxy. Unfortunately, price is a poor proxy for the cost of a sustainable sanitation service for two reasons. Firstly, many sanitation systems are incomplete or badly operated often due to financial, institutional, and societal failures (Evans 1995; Ika *et al.* 2012; International Water Association 2014). Secondly, since sanitation is a public good, willingness to pay is often lower than the economic value of full-service delivery (Ruiters & Matji 2017). For this latter reason, sanitation systems are often supported by public subsidies, either formally through regulated fees or ‘informally’ through systematic underinvestment in maintenance (Evans *et al.* 2009; Perard 2018).

The best-known sanitation costing studies are from the World Health Organization (Hutton & Bartram 2008), the IRC WASHCost Initiative (McIntyre *et al.* 2014), and the World Bank Economics of Sanitation Initiative, or ESI. These all emphasise the importance of reporting the full lifecycle cost of sanitation systems, including costs incurred to design, operate, and maintain them (Fonseca *et al.* 2011; McIntyre *et al.* 2014). Lifecycle costing implicitly assumes a full-costing approach (Burr & Fonseca 2011; Evans & Mara 2011; Daudey 2017), including the direct cost of generating the sanitation service and overheads. In reality, there is a significant ambiguity around the methods used to generate unit cost estimates and particularly the extent to which operations and maintenance costs are reflected in many costing studies (Daudey 2017).

Hutton & Bartram (2008) and World Health Organization (2012) deploy an approach known as **ball-park estimation**. Ball-park estimation is commonly used in infrastructure planning for conceptualisation or pre-feasibility studies (Mislick & Nussbaum 2015) where some level of uncertainty is acceptable; construction projects typically accommodate an uncertainty at this point of around 30% (AACE 2019). Estimations are usually based on the statistical manipulation of historical data in private databases (e.g. the internal information systems of Engineering Procurement Construction – EPC companies) or academic literature (OECD 2007; Loutatidou *et al.* 2014; Hughes *et al.* 2015).

Ball-park estimates from a number of locations both reported by governments and cited in the literature,

particularly the ESI, form the basis for the indicative unit costs estimates in the WHO benefit–cost analysis (Hutton & Haller 2004; Hutton & Bartram 2008; World Health Organization 2012). The economics of sanitation initiative has collected cost estimates based on reporting by government agencies, and household surveys, for a number of countries, see for example, Hutton *et al.* (2014). WASHCost also aimed to generate ball-park cost estimates based on empirical data collection rather than relying on literature. WASHCost reported costs data from water and sanitation projects in rural and peri-urban/small town areas in the state of Andhra Pradesh (India), Burkina Faso, Ghana, and Mozambique. Lifecycle cost estimates were developed for seven types of latrine (Burr & Fonseca 2012).

While WASHCost highlighted the need for standard costing approaches and has played an important role in increasing focus on the significant operational costs of sanitation, there is little evidence that the approach has been used to generate up to date benchmark cost estimates for *urban* sanitation. Neither is WASHCost referenced in the wider infrastructure finance literature; this may be because it uses non-standard cost categories, for example, the term Capital Maintenance Expenditure (CapManEx) which is neither a common accounting term (Roman *et al.* 2012) nor employed in other infrastructure sectors (De Schepper *et al.* 2015; Gatti 2018). The economics of sanitation initiative did generate useful overall cost estimates for some technologies in urban areas (as well as in rural areas) which provide a strong starting point for the current work.

An alternative to ball-park estimation, **analytical estimation** works on the basis of a known or estimated amount of inputs (material, labour, equipment) with known unit costs; the full costs can then be obtained by multiplying one by the other. The CLARA project (Müllegger *et al.* 2014; Ketema & Langergraber 2016) is an example of this approach building up theoretical costs from first principles based on standard bills of quantities (Müllegger *et al.* 2014).

CLARA used empirical data from Burkina Faso, Ethiopia, Kenya, Morocco, and South Africa to develop a simplified analytical costing tool (Müllegger *et al.* 2014; Ketema & Langergraber 2016). The tool can be used to generate cost estimates for sanitation based on local conditions and the Net Present Value of the investment (Ketema *et al.*

2015). The World Bank has used a similar approach in its faecal sludge management (FSM) diagnostic tools (Ross *et al.* 2016).

Analytical estimation works when sufficiently detailed information is available for both quantities and unitary prices of all factors of production (Mislick & Nussbaum 2015), including capital (e.g. land and buildings, and equipment) and labour (Kim *et al.* 2004; Barakchi *et al.* 2017). However, the project management literature emphasises the extent to which analytic estimation can be unreliable particularly for large engineering projects. A number of phenomena tend to lead to over-optimistic estimations (Locatelli 2018). These include optimism bias (Flyvbjerg 2008), strategic misinterpretation (Flyvbjerg 2008), corruption (Locatelli *et al.* 2017), selection biases and winner course phenomenon (Eliasson & Fosgerau 2013), and distortions in tendering (Love *et al.* 2016, 2019). For this reason, some scholars suggest using ball-park estimation for large and complex infrastructure projects, even when detailed analytic data are available (Flyvbjerg 2008; Merrow 2011).

An alternative approach is **parametric cost estimation** (also known as factorial or semi-analytic) costing. This approach recognises that there are critical drivers (parameters) that determine the cost of a service or infrastructure in a given context. The traditional approach to developing parametric cost estimation is to interrogate a large dataset of empirical cost data, employing heuristic formulas to determine the relationship between various parameters and cost values (Mislick & Nussbaum 2015; OECD 2007). In sanitation, some attempts at parametric cost estimation have been made to estimate the nominal costs of different sanitation technologies (Sinnatamby *et al.* 1986; Mara 1996; Mara & Guimarães 1999; Evans & Mara 2011; Eggimann *et al.* 2016a, 2015; Crocker *et al.* 2017; Loetscher & Keller 2018).

Parameters that primarily affect the costs of sanitation systems have been proposed and evaluated by several scholars; these include population densities, size and degree of centralisation (Eggimann *et al.* 2015, 2016b; Eggimann 2016), economies of scale (Hernández-Chover *et al.* 2018), institutional and managerial context (Ika & Donnelly 2017), and other contextual factors such as the technology, labour cost, population density, and topography (Whittington *et al.* 2012; Daudey 2017). Unfortunately, there has been

no systematic attempt to evaluate the relationship between these parameters and cost based on empirical data at the required scale. The results remain specific to isolated contexts or are based on models which have not been empirically validated.

There remain, therefore, significant areas of further research in the arena of sanitation costing, including the need for (Daudey 2017; Eggimann *et al.* 2017):

- Further empirical research to generate a larger database from which both ball-park and parametric estimates could be derived;
- Improvements in the consistency of reporting of cost estimations;
- Further research to assess the full-lifecycle cost of sanitation services, and the differentiation between alternative sanitation technologies, stages of the sanitation value chain and geographical areas; and
- More clarity and transparency concerning the sources of empirical data used in current costing approaches [...]

## THE STANDARD COST METRIC FOR URBAN SANITATION; TACH AND TACC

Responding to the call for greater consistency and for generalisable information about the cost of sanitation, we propose a plausible metric which is comparable across geographies and technologies and also understandable both to professionals in the WASH sector and to municipal managers who make decisions regarding sanitation investments. A useful corollary is the concept of costs per kWh of energy which is comprehensible both to governments, who may have to finance the initial capital investment, and households, who ultimately pay the bills.

For urban sanitation, we propose two cost indicators to express the cost of any sanitation system: TACH and total annualised cost per capita (TACC). TACH/TACC takes into account full lifecycle costs which are annualised and expressed on a per-household or per-user basis.

The key question in any infrastructure investment is the total level of financial liability that the planned investment is likely to generate compared to total sources of income (which are limited to tariffs, tax revenue, and transfers

from central government or development partners). The liability associated with the proposed investment includes both the costs of capital (the investment, plus the financing costs if any) plus the operational costs over the full lifetime of the project, the lifecycle cost reported by Fonseca *et al.* (2011). Operational costs for some systems are often excluded from a discussion of the relative costs of different systems – possibly since they are assumed to be covered by households (fees charged by operators who empty onsite pit latrines and tanks are an example). However, we argue that information on the full-cost liability is essential to enable municipal decision-makers to incorporate sanitation investments into municipal budgeting. Full-cost information facilitates the development of plans to sustainably cover all the costs that are associated with the planned investment; in the absence of this full cost information, operational costs are often underestimated or omitted, with resultant underfunding and system failure.

However, the total lifecycle cost is effectively meaningless at the local government level, where budgets are managed on an annual basis. For this reason, it makes the most sense to convert this to an annual liability, covering debt service for capital investment plus the annual operational costs and periodic maintenance requirements.

To enable comparison across various scales of systems, the total number of people directly using the service is used as the denominator. The choice of household or capita for the denominator is challenging – each has merit. Per capita costs are perhaps most useful when looking at national level macro-economic performance, or when comparing expenditure on sanitation against that on say the police force, but some local governments rely on property tax for their revenue, and water and sewerage utilities bill on a household basis. For many decision-makers therefore using the household as a denominator makes the most sense.

## A PROPOSED APPROACH TO COST ESTIMATION

In selecting an approach to use in estimating the TACH or TACC for any given system in a given place, there is a trade-off between precision, reliability, and level of detail on the one hand, and availability of data and resources on

the other. The focus here is on supporting local decision-makers to make credible plans quickly and cheaply, selecting the best technical options in a given context (Mitlin 2015). This requires costing data that are reliable, comparable, and easy to make locally relevant (Kalbermatten *et al.* 1982). We rejected analytic estimation on the basis that it has very high information requirement, and consequently high cost, yet remains prone to bias (Flyvbjerg *et al.* 2018; Love *et al.* 2019).

Instead, the proposed approach to cost estimation in the CACTUS project is to develop a parametric estimation tool that could generate plausible cost estimates for a range of sanitation technologies and systems in any given context based on the known values of these key parameters.

From earlier reviews, several key contextual parameters have been identified as candidates in determining the relative cost of different sanitation systems. These are scale (size of city and size of the sanitation system); population density; topography; and geographical location (as a proxy for relative costs of inputs such as labour, materials, fuel) (Whittington *et al.* 2012; Eggimann *et al.* 2015, 2016b; Eggimann 2016; Daudey 2017; Ika & Donnelly 2017; Hernández-Chover *et al.* 2018).

Having identified a set of candidate parameters for cost estimation purposes, the next task is to assemble a reliable database which could be used to develop the heuristics needed for the estimation approach to work. As already mentioned, data are scarce. Consequently, an important element of our work is the collection of new data on which to base our estimations.

Some specific challenges arise, however, in the collection and organisation of urban sanitation cost data. Urban sanitation services are provided by a compound of capital-intensive infrastructure, operational management, and ongoing interventions, including capacity building, advocacy, and other promotional activities all of which happen along the sanitation 'value chain'. With the exception of fully operational sewered networks, very few urban sanitation chains are operated by a single operator 'end to end', and many sanitation systems are not fully functional. Cost data reported by operators are often therefore only a partial representation of the real costs of delivery of safely managed sanitation. To address these challenges, we set out to build a database of cost information that could be

used to estimate the full costs of service delivery for the entire value chain. To achieve this, we developed an NBPRA for sanitation.

## NBPRA FOR SANITATION

The NBPRA facilitates the collection and collation of data in a consistent format from operators who are delivering ongoing sanitation services. Cases are selected from a broad range of contexts (covering a wide range of parameters) and a range of different sanitation technologies and approaches.

The approach is standardised and based on four main pillars, namely (1) technological homogeneity, (2) acceptable service, (3) basic costing assumption, and (4) the reference business model. Cost data are then normalised to comparable currency equivalent values, annualised, and divided by the household/people served, so they can be reported as TACH/TACC.

### Technological homogeneity

The NBPRA is exclusively concerned with a subset of 'safely managed' sanitation as defined by the Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP), namely systems which guarantee that households use 'an improved type of sanitation facility that is not shared with other households and the excreta ... [is] transported and treated off-site.' (UNICEF & WHO 2019). In reality, many systems that use appropriate technologies are incomplete, for example, faecal sludge which is transported but then dumped in the environment (Peal *et al.* 2020). The NBPRA is designed to accommodate empirical data collected from projects and programs that only deliver partial services (toilets connected to septic tanks, for example, or an emptying service). Cost estimates generated for these partial sanitation systems can be added together to generate cost estimates for complete sanitation systems. To enable this summing, partial service types need to be clustered into meaningful technology categories which are internally consistent, externally comparable in technological terms, and amenable to interpretation by both sanitation experts and the wider community of decision-makers.

The NBPRA, therefore, uses a set of standard ‘components’ definitions, each of which maps to a single ‘element’ of the sanitation value chain (containment, emptying, transport, treatment, etc.). The ‘components’ were selected to reflect the most common technological approaches to deliver networked (urban) sanitation. Components are based on [Tilley \*et al.\* \(2014\)](#) but have been bundled somewhat to reduce complexity and facilitate a meaningful comparison on a cost basis. We use general terminology, recognising that specific local terms are often used but that these often have different meanings in different locations (for example, despite the existence of a globally recognised technical definition, the terms ‘septic tank’ and ‘pit latrine’ often have a different precise connotation in different places and we therefore avoid their use here).

For wastewater systems, we assume that the main technological driver of the cost relates to the nature of the sewer network specifically;

- Conventional versus simplified networks;
- Combined versus separate networks;
- Pumped versus gravity-dependent networks.

Combining these options leaves a set of eight component types for emptying and transport in wastewater based systems (see [Figure 1](#)).

For systems which rely on pits or tanks (often referred to as ‘onsite’ or FSM systems) and container-based systems, we differentiate four main types of component at the containment (household) end of the sanitation value chain (sealed tank with an infiltration structure, sealed tank without an infiltration structure, infiltrating pit, and container for container-based systems). Moving excreta from these systems can either take place in two steps (emptying plus transport) or in a single operation (typically where a single truck is used to empty the tank and transport the contents away to treatment). In either case, we make a distinction between manual powered systems and externally powered systems ([Figure 1](#)).

For treatment, we have distinguished between aerated and anaerobic systems for both wastewater and faecal sludge, and in the case of wastewater, we further distinguish between passive and powered aeration. A summary of the 27 final component types is shown in [Figure 1](#).

## Acceptable service

Many otherwise ‘appropriate’ sanitation systems fail due to underfunding, for example, sewer systems that leak due to low maintenance ([Peal \*et al.\* 2020](#)). These funding gaps can be identified and filled, when sufficient empirical data are available, through modelling, to give a clear idea of the full costs of the system if it were to be properly operated and maintained.

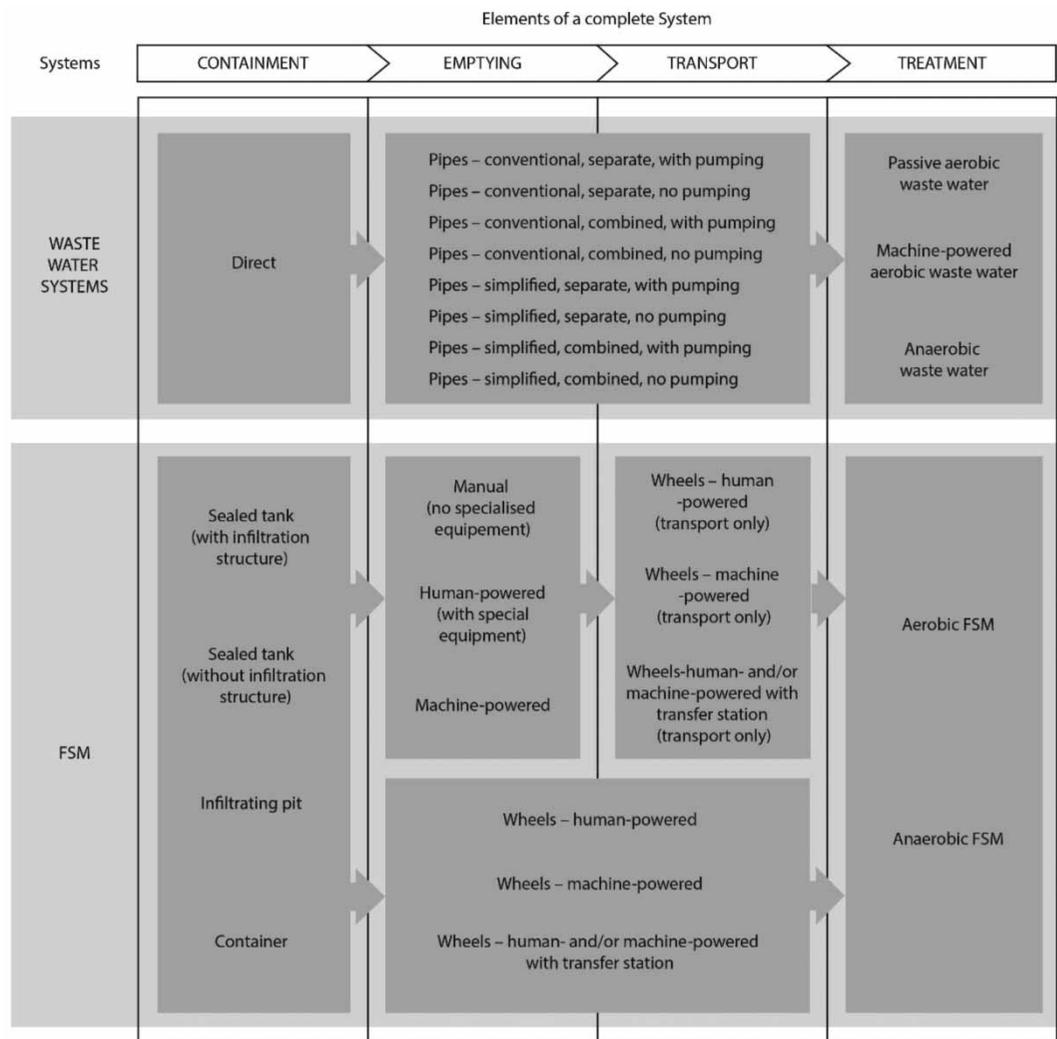
Clearly, there are variations in the ‘level of service’ provided by different sanitation systems – private, shared, community, and public toilets offer a wide range of levels of amenity to users ([Evans \*et al.\* 2017](#)); different treatment options will perform differently in terms of efficiency ([Choudhury & Saha 2017](#); [Lutterbeck \*et al.\* 2017](#)), environmental impact, embodied energy waste recovery ([Cornejo \*et al.\* 2013](#)), resilience ([Luh \*et al.\* 2017](#)), and sustainability ([Zurbrügg \*et al.\* 2014](#)).

These aspects of the sanitation system performance are important. However, rather than internalising them resulting in greater complexity and less transparency, the NBPRA explicitly excludes them. The aim is to generate reliable comprehensive cost estimates for systems that deliver ‘safely managed sanitation’ to which decision-makers may choose to add other performance criteria when making real-world technology selections.

## Basic costing assumption

The NBPRA is a full-costing approach ([Arnaboldi \*et al.\* 2014](#)), generating cost data which can subsequently be used for capital budgeting and focused on the financial cost ([Roman \*et al.\* 2012](#); [Arnaboldi \*et al.\* 2014](#)). Data are reported in terms of the ‘industrial cost’, i.e. the full cost of sanitation service consisting of both the direct and indirect cost of building and operating sanitation infrastructure, plus administrative charges, the cost of financing, and taxation.

The costs associated with any component are categorised using a standard proforma to facilitate both data collection (acting as a checklist for enumerators), data verification, and modelling of incomplete data (for example, where an operator cannot or will not report the cost of land, or where taxes and fees are not paid). Cost categories used within the NBPRA are shown in [Table 1](#).



**Figure 1** | Components of a sanitation system for use in CACTUS cost estimation, distinguishing between systems that predominantly rely on pipes to transport excreta in the form of wastewater, and all other systems which are often loosely categorised as faecal sludge management (FSM)-based systems.

## Reference business model

Sanitation services can be provided via a wide range of business models with varying degrees of centralisation, and aggregation along the value chain. Because of this complexity, there is a challenge in reporting on the basis of a standardised unit of analysis consistent in regard to (1) number and types of transactions, (2) ownership structure, and (3) organisational structure (Williamson 1979, 1981). Variations in these characteristics introduce distortions in the reporting of empirical data jeopardising their reliability and the ability to create a consistent sample of cost benchmarks.

To overcome this challenge, the NBPRA assumes:

1. There is a 'virtual' organisation responsible for operating the entire sanitation system herein called the unique operator;
2. The unique operator owns all the sanitation infrastructure. The operator finances the sanitation infrastructure and borrows all or part of the capital on the financial market at market value;
3. The unique operator buys (at market value) all the factors of production that are necessary to generate sanitation services across the entire sanitation value chain;
4. The unique operator hires and manages all necessary labour (direct and indirect) for generating the sanitation services across the entire sanitation value chain.

**Table 1** | Standard CACTUS framework for reporting costs of urban sanitation

| Cost voice                            | Examples  |
|---------------------------------------|---|
| <b>Capital costs – CAPEX</b>          |   |
| Land                                  | <i>Land purchase</i>  |
| Infrastructure and building equipment | <i>Buildings, fixed plant purchase</i>  |
| Equipment                             | <i>Plant and vehicle purchase</i>   |
| Staff development                     | <i>Vaccinations, one off training</i>   |
| Major and extraordinary repairs       |   |
| Other CAPEX                           |   |
| Administration charges                |   |
| Financing                             |   |
| Taxes                                 |   |
| <b>Operational costs – OPEX</b>       |   |
| Land                                  | <i>Land rental</i>  |
| Infrastructure and building equipment | <i>Leasing costs for buildings and fixed plant</i>  |
| Equipment                             | <i>Leasing costs, operational costs</i>   |
| Staffing                              | <i>Salaries, pensions, health insurance</i>   |
| Consumables                           | Services includes: Consulting/<br>advisory, Legal, Insurance,<br>Regular Maintenance, other |
| - Utilities                           |   |
| - Fuel                                |   |
| - Chemicals                           |   |
| - Services                            |   |
| - Other                               |   |
| Other OPEX                            |   |
| Administration charges                |   |
| Financing                             |   |
| Taxes                                 |   |

These principles introduce an archetypical business model that never materialises in real life but enables the cost data that are collected to be used to generate costs for a range of complete sanitation systems which are applicable irrespective of the actual business model context.

A key outcome of this approach is that revenue streams and transfers between operators of different elements of the sanitation system (for example, payment by a truck operator when dumping at a treatment plant) are excluded. They are exogenous to the actual costs of implementing the safely managed sanitation service and do not correspond to any industrial activity for the generation of the sanitation service.

As an example, taking a typical FSM system based on sealed tanks at household level, the following ‘industrial’ costs are included:

1. The cost of the sanitation infrastructure which includes the household toilet and the associated substructure (in this case a sealed tank), emptying and conveyance equipment (e.g. vacuum tank), transfer station (if any), and a treatment plant. These include the cost of financing infrastructure (e.g. the interests and fees paid to financial institutions for the construction and operation of sanitation infrastructure). This cost is part of the CAPEX;
2. The direct cost of operating the sanitation infrastructure, including the input supplies (e.g. fuel for the vacuum truck), consumables and wages (e.g. the labour required to clean and maintain the toilet, emptying the containment technologies, drive the vacuum truck, and discharge and treat the faecal sludge). This cost is part of the OPEX;
3. The cost of indirect facilities (e.g. office space, parking lot, etc.) and equipment (e.g. phones, computers) employed by the unique operator to run the sanitation system. This cost is part of the CAPEX;
4. The indirect cost of running the sanitation system, including annual expense on marketing and administration, licenses, public concession for the sanitation service, etc. This cost is part of the OPEX.

### Normalisation process

In CACTUS, empirical data are collected from a wide variety of locations, for sanitation systems that have varying life expectancy and technical characteristics. To facilitate the parametric cost estimation in the future, these costs are converted to a standard reporting year and currency and annualised, to generate a comparable annual cost liability in each case.

Currency conversion generates costs in terms of International \$ 2018 (Int\$ 2018), based on the Consumer Price Index using Purchasing Power Parity (Rao 2001; Lakner et al. 2018). Conversion factors are based on the World Bank Database (World Bank 2020).

Annualisation is applied in line with Stewart et al. (1995). The cost is expressed as the Equivalent Annual

**Table 2** | Cost per household for sanitation components based on empirical and secondary data sources

| Element    | Component              | Total annualised cost per household (TACH) (Int\$ 2018) |                                     |            |            |     | Annualised CAPEX per household (Int\$ 2018) |        |            |           |     | Annual OPEX per household (Int\$ 2018) |        |            |           |     |     |     |
|------------|------------------------|---|-------------------------------------|------------|------------|-----|---|--------|------------|-----------|-----|--|--------|------------|-----------|-----|-----|-----|
|            |                        | n   | Median                              | Mean       | Min        | Max | n   | Median | Mean       | Min       | Max | n                                      | Median | Mean       | Min       | Max |     |     |
| Wastewater | Containment            | Direct  | 1                                   | <b>362</b> | 362        | 362 | 362   | 6      | <b>94</b>  | 103       | 34  | 233                                    | 1      | <b>130</b> | 130       | 130 | 130 |     |
|            | Emptying and transport | Pipes – conventional, separate, with pumping            | 5                                   | <b>195</b> | 395        | 107 | 832   | 5      | <b>164</b> | 296       | 60  | 668                                    | 5      | <b>61</b>  | 99        | 31  | 195 |     |
|            |                        | Pipes – conventional, separate, no pumping              | –                                   | No data    |            |     |   | 1      | <b>704</b> | 704       | 704 | 704                                    | –      | No data    |           |     |     |     |
|            |                        | Pipes – conventional, combined, with pumping            | 7                                   | <b>287</b> | 294        | 93  | 515   | 7      | 265        | 263       | 75  | 473                                    | 7      | <b>37</b>  | 31        | 17  | 42  |     |
|            |                        | Pipes – conventional, combined, no pumping              | –                                   | No data    |            |     |   | –      | No data    |           |     |  | –      | No data    |           |     |     |     |
|            |                        | Pipes – simplified, separate, with pumping              | –                                   |            |            |     |   | –      |            |           |     |  | –      |            |           |     |     |     |
|            |                        | Pipes – simplified, separate, no pumping                | –                                   |            |            |     |   | –      |            |           |     |  | –      |            |           |     |     |     |
|            |                        | Pipes – simplified, combined, with pumping              | –                                   |            |            |     |   | –      |            |           |     |  | –      |            |           |     |     |     |
|            |                        | Pipes – simplified, combined, no pumping                | –                                   |            |            |     |   | –      |            |           |     |  | –      |            |           |     |     |     |
|            |                        | Treatment   | Passive aerobic waste water         | 6          | <b>28</b>  | 53  | 11  | 148    | 7          | <b>8</b>  | 64  | 1                                      | 282    | 7          | <b>10</b> | 21  | 1   | 80  |
|            |                        |   | Machine-powered aerobic waste water | 15         | <b>134</b> | 159 | 58  | 315    | 15         | <b>99</b> | 106 | 21                                     | 239    | 15         | <b>54</b> | 54  | 2   | 131 |
|            | Anaerobic waste water  |   | –                                   | No data    |            |     |   | –      | No data    |           |     |  | –      | No data    |           |     |     |     |

*(continued)*

Table 2 | continued

| Element                        | Component              | Total annualised cost per household (TACH) (Int\$ 2018)                       |        |            |     |     | Annualised CAPEX per household (Int\$ 2018) |                |           |     |     | Annual OPEX per household (Int\$ 2018) |                |            |     |     |     |
|--------------------------------|------------------------|---|--------|------------|-----|-----|---|----------------|-----------|-----|-----|--|----------------|------------|-----|-----|-----|
|                                |                        | n   | Median | Mean       | Min | Max | n   | Median         | Mean      | Min | Max | n                                      | Median         | Mean       | Min | Max |     |
| Faecal Sludge Management (FSM) | Containment            | Sealed tank (with infiltration structure)                                     | –      | No data    |     |     |   | –              | No data   |     |     |  | –              | No data    |     |     |     |
|                                |                        | Sealed tank (without infiltration structure)                                  | 3      | <b>87</b>  | 84  | 67  | 97  | 8              | <b>39</b> | 52  | 8   | 165                                    | 3              | <b>28</b>  | 34  | 26  | 49  |
|                                |                        | Infiltrating pit  | 4      | <b>63</b>  | 95  | 30  | 223   | 4              | <b>63</b> | 95  | 30  | 223                                    | 4 <sup>a</sup> | <b>0</b>   | 0   | 0   | 0   |
|                                | Emptying               | Container   | 2      | <b>115</b> | 115 | 106 | 123   | 2              | <b>47</b> | 47  | 34  | 61                                     | 2              | <b>67</b>  | 67  | 62  | 72  |
|                                |                        | Manual (no specialised equipment)   | 2      | <b>82</b>  | 82  | 48  | 116   | 2 <sup>b</sup> | <b>4</b>  | 4   | 0   | 9                                      | 2              | <b>78</b>  | 78  | 48  | 107 |
|                                |                        | Human-powered with specialised equipment                                      | 2      | <b>25</b>  | 25  | 23  | 27  | 2              | <b>0</b>  | 0   | 0   | 0                                      | 2              | <b>25</b>  | 25  | 22  | 27  |
|                                | Emptying and transport | Machine powered   | –      | No data    |     |     |   | –              | No data   |     |     |  | –              | No data    |     |     |     |
|                                |                        | Wheels – human-powered  | 2      | <b>136</b> | 136 | 109 | 163   | 2              | <b>2</b>  | 2   | 1   | 3                                      | 2              | <b>134</b> | 134 | 108 | 160 |
|                                |                        | Wheels – machine-powered  | 11     | <b>28</b>  | 29  | 3   | 83  | 11             | <b>5</b>  | 7   | 1   | 32                                     | 13             | <b>13</b>  | 19  | 0   | 51  |
|                                | Transport              | Wheels – human- and/or machine-powered with transfer station                  | 1      | <b>83</b>  | 83  | 83  | 83  | 1              | <b>1</b>  | 1   | 1   | 1                                      | 1              | <b>82</b>  | 82  | 82  | 82  |
|                                |                        | Wheels – human-powered (transport only)                                       | –      | No data    |     |     |   | –              | No data   |     |     |  | –              | No data    |     |     |     |
|                                |                        | Wheels – machine-powered (transport only)                                     | 1      | <b>26</b>  | 26  | 26  | 26  | 1              | <b>8</b>  | 8   | 8   | 8                                      | 1              | <b>17</b>  | 17  | 17  | 17  |
|                                | Treatment              | Wheels – human- and/or machine-powered with transfer station (transport only) | 1      | <b>1</b>   | 1   | 1   | 1   | 1              | <b>1</b>  | 1   | 1   | 1                                      | 1              | <b>1</b>   | 1   | 1   | 1   |
|                                |                        | Aerobic FSM   | 5      | <b>17</b>  | 36  | 0   | 103   | 5              | <b>5</b>  | 9   | 0   | 25                                     | 6              | <b>9</b>   | 23  | 0   | 94  |
|                                |                        | Anaerobic FSM   | 3      | <b>44</b>  | 47  | 11  | 87  | 3              | <b>21</b> | 31  | 4   | 69                                     | 3              | <b>17</b>  | 16  | 7   | 23  |

<sup>a</sup>For all data points for 'infiltrating pits', OPEX is reported or assumed to be zero.

<sup>b</sup>One data point of 'manual (no specialised equipment)' is reported to be zero.

Cost (EAC) of owning, operating, and maintaining the sanitation system (or sub-system) over its entire lifecycle. In other words, it is the annual expenditure needed to cover the servicing of capital debt required to construct and maintain the system plus the annual operational budget.

The EAC is calculated, as shown in Equation (1).

EAC (Sanitation System or Subsystem)

$$= \frac{k_r \cdot \sum_{t=0}^T \frac{\text{COST}_t \cdot k_r}{(1+k_r)^t}}{1 - (1+k_r)^{-T}} \quad (1)$$

where:

- $\text{COST}_t$  are the costs incurred during the lifecycle (i.e.  $T$ ) associated with the data point considered.

- $T$  = represents the longest lifecycle associated with the data point considered, and it is calculated in years.  $T$  corresponds to the longest lifetime of the infrastructures associated with the data point;
- $kr$  = real interest rate, which is calculated using the following formula (Equation (2))

$$k_r = \frac{k_n - s}{1 + s} \quad (2)$$

where

- $k_n$  = nominal interest rate, assumed 5% as the social discount rate.
- $s$  = annual inflation in the country considered.

**Table 3** | Synthesised cost range estimates from the CACTUS database, for example, archetypal sanitation systems with no parameterisation

| Archetypal sanitation system  | Total annualised cost per household by system element and for whole system (Int\$ 2018) |   |           |   |                 |
|---|---|---|-----------|---|-----------------|
|   | Median (Minimum–maximum)  |   |           |   |                 |
|   | Containment   | Emptying  | Transport | Treatment   | Whole System    |
| Container-based sanitation, with mechanised emptying and transfer stations, with composting (aerobic treatment) | Container<br>$n = 2$<br><br>115 (106–123)   | Wheels – human and/or machine powered with transfer station <sup>a</sup><br>$n = 1$<br><br>83 (83–83) |           | Aerobic FSM<br>$n = 5$<br><br>17 (0–103)                            | 215 (189–309)   |
| Onsite ‘septic’ tanks, mechanised emptying and transport with anaerobic treatment                               | Sealed tank without infiltration structure<br>$n = 3$<br><br>87 (67–97)                 | Wheels – machine powered<br>$n = 11$<br><br>28 (3–83)   |           | Anaerobic FSM<br>$n = 3$<br><br>44 (11–87)                          | 159 (81–267)    |
| Onsite ‘septic’ tanks, mechanised emptying and transport with anaerobic treatment (Africa only)                 | Sealed tank without infiltration structure<br>$n = 3$<br><br>87 (67–97)                 | Wheels – machine powered<br>$n = 3$<br><br>30 (28–83)   |           | Anaerobic FSM <sup>a</sup><br>$n = 1$<br><br>11 (11–11)             | 128 (106–191)   |
| Sewerage, conventional, combined, pumped, with activated sludge treatment                                       | Direct <sup>a</sup><br>$n = 1$<br><br>362 (362–362)                                     | Pipes – conventional, combined, with pumping<br>$n = 7$<br><br>287 (93–515)                           |           | Machine-powered aerobic waste water<br>$n = 15$<br><br>134 (58–315) | 783 (513–1,192) |

<sup>a</sup> $n = 1$  data have very high uncertainty and cannot be cross checked.

In calculating the EAC, most capital expenditures are considered as one-off expenses at time zero, except major and extraordinary repairs, which are considered cyclical with a period longer than one year. Operational expenditures are always expressed on an annual basis and are assumed fixed during the period *T*.

**Generation of TACH and TACC estimates**

TACH/TACC is calculated by dividing the EAC by the estimated number of households or people served. To aid interpretation, EAC can be calculated for CAPEX and OPEX jointly or separately. This may be useful where capital liability is carried by a different government entity than operational liability for example. The reporting unit is International \$(2018) per household per year, or per person per year.

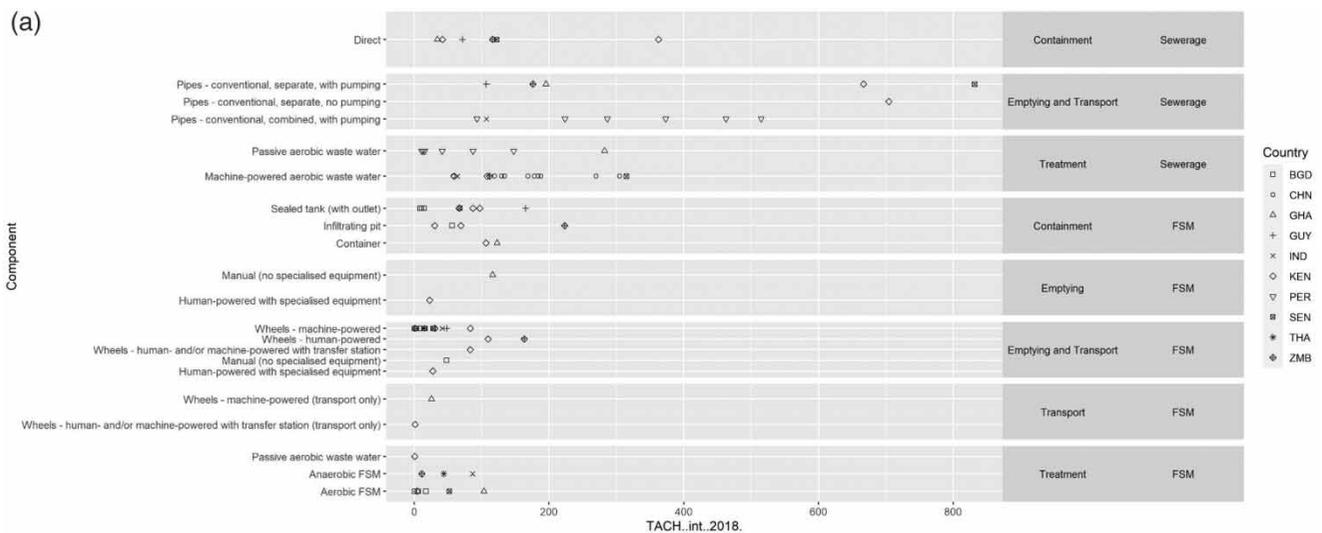
**RESULTS**

The NBPRA has been tested in 25 cities in 10 countries, collecting data on 87 individual sanitation components. A summary of the data collected and processed to date is shown in Table 2.

**What the preliminary results mean**

Typical cost liabilities of full sanitation systems of a particular type can be assessed from CACTUS data by summing indicative costs of a set of relevant components (to account for containment, emptying, transport, and treatment). To demonstrate how these can be constructed, examples of estimated cost ranges for synthetic sanitation systems are shown in Table 3. Median data are preferred to means due to the heavy skewing that can result from a single outlying data point. Further break downs of the data are possible – for example, in Table 3, we also show selected data for onsite systems in Africa. Estimates of TACH for complete systems have high levels of uncertainty at this stage in the process due to the small sample sizes and clustering of case studies. The data come from 25 cities, representing only a small sample of the conditions under which urban sanitation systems are implemented.

As might be expected, TACH for the sewerage system shown in Table 3 is significantly higher than TACH for container-based or onsite sanitation systems. However, in Figure 2, we present the data sorted by country, and showing both total costs and CAPEX/OPEX cost breakdown, all annualised on a per household basis. While seweraged sanitation systems are often said to be ‘more



**Figure 2** | (a) Total annualised cost per household for sanitation components based on empirical and secondary data in the CACTUS database (*n* = 71). (b) Annualised CAPEX per household for sanitation components based on empirical and secondary data in the CACTUS database (*n* = 83). (c) Annual OPEX per household for sanitation components based on empirical and secondary data in the CACTUS database (*n* = 75). (continued).

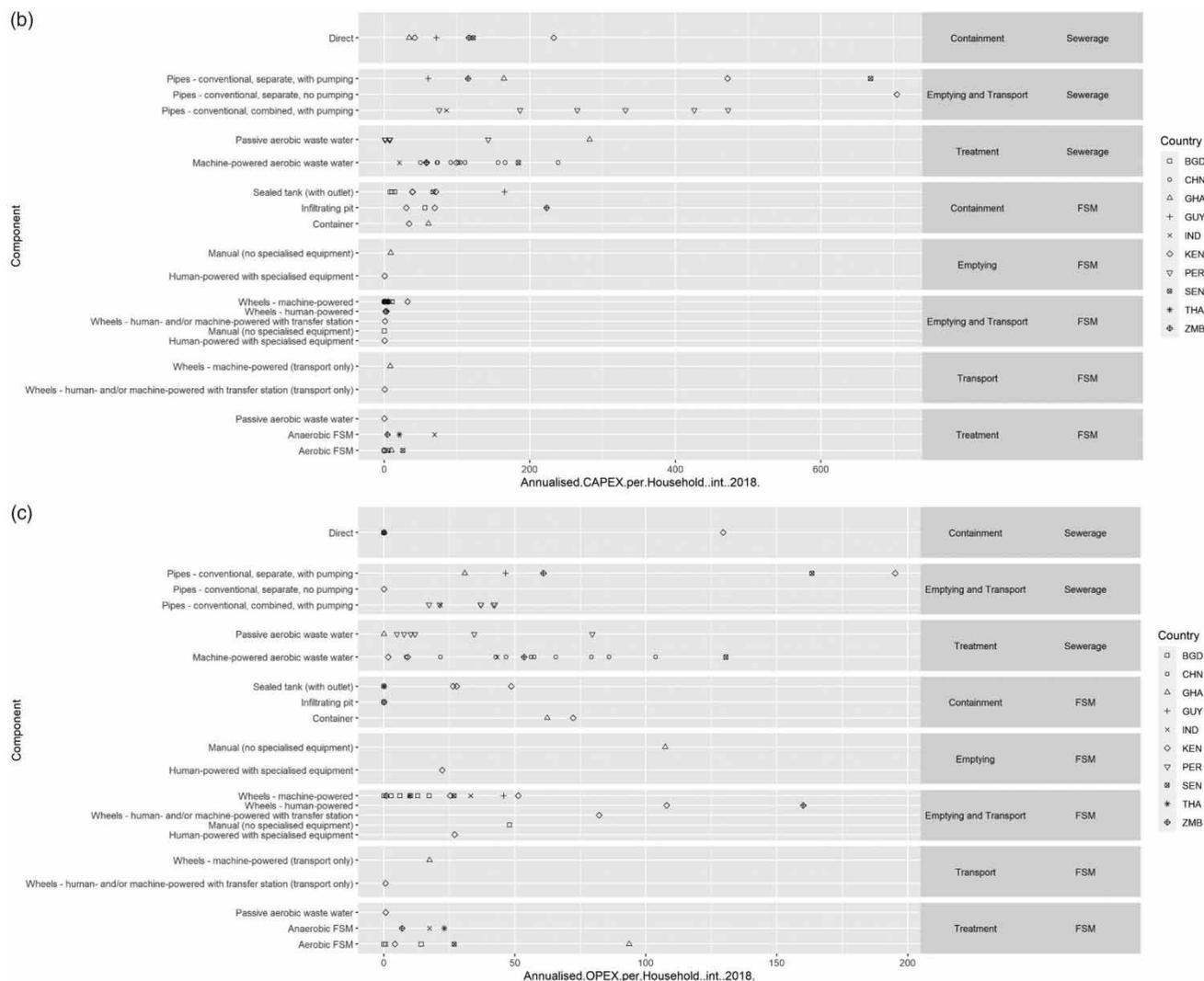


Figure 2 | (continued).

expensive' than FSM-based systems, a closer inspection of the data suggest that the situation may be more complex. For example, the operational liabilities of sewers may sometimes be lower than those for road-based transportation of faecal sludge under some conditions (see Figure 2(b)). Returning to Table 2, it is also possible to see that TACH for container-based systems is dominated by operational costs whereas onsite systems and sewers have a much higher CAPEX dependency. In all these cases, care is necessary because of the aforementioned clustering of data points.

### Candidate cost drivers for parametric estimation

Figure 2 shows that for some systems, TACH clusters by country (see, for example, that the data for mechanised aerobic treatment of wastewater are higher in the China cases than in the other three countries for which data are reported). A much larger dataset will be required to properly understand the combination of factors which drive differing cost performance in each case. While the geographical location is likely to be one driver (as it will determine for example the relative costs of materials, fuel,

and labour) other factors, including the scale of the system, population density, and topography are also highly likely to drive costs variation. A significant increase in the data held in the CACTUS database is needed in order to fully interrogate the cost drivers.

### Reflections on data collection

Figure 2 shows wide cost ranges for many of the components for which data have been collected. The NBPRA approach has proved robust at driving the collection of reasonably complete empirical data on costs, although many operators are unable to fully report on their cost liabilities. For older systems, there is often a lack of data on capital costs, and for newer systems, a lack of data on operational costs. In addition, many operators are not aware of certain implicit subsidies (for example, non-payment of electricity bills issued by national energy-generating organisations). However, the standardised data collection approach has shown promise in helping to drive up the quality of data that is collected. In addition, as the dataset grows, it would become possible to correct for omitted data (for example, by understanding typical cost distributions for particular systems under particular conditions). This type of correction may result in more accurate, clustered estimates of TACH for particular contexts.

### CONCLUSION

Compared to other infrastructure sectors, there is a dearth of reliable, internationally comparable cost data for urban sanitation. Sanitation scholars have used both ball-park and analytical cost estimation approaches, and there have been some localised or specific efforts to generate models for parametric estimation. In the absence of reliable global data, the full costs of sustainable implementation or urban sanitation are being systematically underestimated (Flyvbjerg 2008).

This research considers the lessons learned in other sectors in addressing similar costing challenges and proposes a strategy for developing bespoke parametric cost estimation models to favour easy and reliable cost estimation, for alternative sanitation technologies, in a range of contexts.

Two key requirements of such an approach are the development of standard costing metrics and the development of a large and coherent empirical dataset of sanitation technology cost estimates selected from a range of geographical context and sanitation technologies.

The main contribution to knowledge to date comprises the proposition of the TACH – TACH – and per capita – TACC, costing metrics, which are foundational to CACTUS. The preliminary data collection, based on a standardised approach known as NBPRA, has generated an empirical data set which is larger than any that we have so far been able to find but not yet large enough to form the basis of a reliable global parametric approach to cost estimation.

Further work is proposed to increase the data contained in the CACTUS database and start to develop heuristics to understand how key cost drivers interact to determine the relative costs of different sanitation systems in a range of contexts. The CACTUS database is intended to become a public repository for empirical sanitation cost data which will facilitate future planning.

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### DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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