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An evaluation of different provision strategies for scaled-up container-based sanitation

Charlie Ferguson[a], Adrian Mallory[a], Paul Hutchings[b], Claire Remington[c], Erica Lloyd[c], Domenic Kiogora[d], Fiona Anciano[e] and Alison Parker[a,*]

[a] Cranfield Water Science Institute, Cranfield University, Cranfield, UK
[b] School of Civil Engineering, University of Leeds, Leeds, UK
[c] SOIL Haiti, Cap-Haïtien, Haiti
[d] School of Pure and Applied Sciences, Meru University of Science and Technology, Meru, Kenya
[e] Department of Politics, University of Western Cape, Cape Town, South Africa
*Corresponding author. E-mail: a.parker@cranfield.ac.uk

CF, 0000-0003-4183-3300; PH, 0000-0002-7758-4644; CR, 0000-0003-0459-7177; EL, 0000-0003-3666-9702; FA, 0000-0002-8613-1452

ABSTRACT

Container-based sanitation (CBS) is increasingly used to provide safely managed sanitation in low-income urban settlements. However, questions remain around the viability of scaling up the technology, partly because it relies on regular emptying and servicing of containers by a CBS provider. This paper investigates mechanisms by which this process can be achieved efficiently. Three separate collection strategies are evaluated for their routing efficiencies as CBS goes to scale. An open-source route optimisation solver determines the constituent driving and walking distances necessary for each strategy and has been applied in areas of Cape Town, Cap-Haïtien, Lima and Nairobi. The results indicate that with fewer users (e.g. 50) transfer station models offer the shortest driving routes. However, these do require users to carry their containers (e.g. up to 170 m when stations are 100 m apart). As the number of users increases (e.g. to 5,000), visiting individual houses from a neighbourhood depot offers increasingly efficient driving distances. Overall, however, the results suggest that economies in collection distances for scaled CBS will be largely conditional on greater vehicle capacity (rather than any particular provision strategy). This highlights the importance of road access throughout low-income urban settlements in providing a viable CBS service at scale.

Key words: faecal sludge management, road networks, route optimisation, urban sanitation, WASH

HIGHLIGHTS

- Container-based sanitation is a form of road-based faecal sludge management.
- Efficient routing of collection vehicles is critical for enabling scaled CBS.
- This modelling evaluates three existing provision strategies using Google-OR tools.
- Transfer stations and depots within neighbourhoods can reduce the required driving.
- However, enlarged vehicle capacity offers greatest reductions in collection routing.

INTRODUCTION

The emergence of SARS-CoV-2 has exacerbated a global sanitation crisis. Over a quarter of the world's population lacks access to household-level systems that safely contain and treat excreta (WHO & UNICEF 2019). Approximately 2.8% of total global deaths can be attributed to inadequate water sanitation and hygiene (WASH; Prüss-Ustün *et al.* 2019). With over a billion people required to leave their households to meet their sanitation needs, the emergence of SARS-CoV-2 has highlighted concerns around shared toilets (Caruso & Freeman 2020). These concerns already include evidence demonstrating such communal facilities exacerbate security issues for women (Corburn & Hildebrand 2015; Caruso *et al.* 2017).

Despite these fears, the use of shared facilities has expanded in urban areas across many less-developed regions in recent years (Shiras *et al.* 2018; Foggitt *et al.* 2019). This expansion looks set to continue with an extra 2.3 billion people expected to live in these environments by 2050 (UNDESA 2018). On-grid sanitation solutions (e.g. household sewers) are not expanding rapidly enough to meet this demand (Öberg *et al.* 2020).

Over the last decade, container-based sanitation (CBS) has emerged as a potential off-grid technology to combat the challenge of safely managing excreta for the world's growing urban population (Mackinnon *et al.* 2018). CBS involves the containment of faeces within sealable containers (typically separating urine and faeces) which are then collected from individual households and transported to a waste processing site to be treated (Tilmans *et al.* 2015). The flexibility of such systems can have benefits in impoverished urban communities with high levels of flood risk and low rates of land ownership (Scott *et al.* 2015).

Any sustainable provision of CBS relies on a series of tasks being regularly performed by a 'CBS provider' (e.g. a social enterprise, a non-governmental organisation, municipality, etc.). Together these processes are referred to as the CBS service chain, of which Figure 1 gives the constituent 'operational' procedures (i.e. from containment through to the re-use of waste). There are numerous potential barriers to building a viable CBS service chain, ranging from the health concerns over hand-held transfer of waste containers (Mackinnon *et al.* 2018) to the favourability of market conditions for any re-use products (Mikhael *et al.* 2017). This typifies the broader discussion on the sustainability of sanitation systems, where the complexity of interacting factors in determining long-term viability of WASH infrastructure has been recognised (Lundin *et al.* 1999; Iribarnegaray *et al.* 2015; Hashemi 2020). The sustainability of off-grid sanitation systems, particularly when resource recovery is an objective, is dependent on viability along the entirety of the service chain (Silveti & Andersson 2019).

While in no way dismissing the breadth of challenges faced when building (and expanding) a sustainable CBS service chain, this paper focuses on only one component – the ability of CBS providers to efficiently navigate the road networks of neighbourhoods they serve as their service goes to scale.

This is a critical issue for CBS providers because regular neighbourhood visits are necessary for the safe and hygienic collection of waste. This reflects wider recognition in the literature that the operational efficiency of transport arrangements is a major barrier for road-based faecal sludge management (FSM) systems (Kennedy-Walker *et al.* 2016; Balasubramanya *et al.* 2017). It is worth noting also that regular visits by a CBS provider are beneficial for fostering positive relationships with the community being served (Moya *et al.* 2019).

This research paper examines the routing efficiencies available from three practised provision strategies across four neighbourhoods where CBS is currently being employed. This entails using a hypothetical, scenario-based approach which, with the technology's acknowledged role in achieving the Sustainable Development Goals (World Bank Group 2019), offers useful critique of CBS's robustness to scaling sustainably.

METHOD

This research evaluates the routing efficiencies achieved by different CBS provision strategies under multiple usage projections in four separate neighbourhoods. A description of the different case study areas will be followed by a discussion of how the CBS strategies will be characterised and evaluated.

Study sites

The Container-Based Sanitation Alliance (CBSA) has members providing a CBS service in six cities. Three of these cities were selected to be included in this study (providing wide geographic spread). A fourth, Cape Town, was also included as host of one of the largest existing CBS projects. This paper focuses on a neighbourhood within each city: (i) BM Section in Cape Town; (ii) Fosen Michel in Cap-Haïtien; (iii) Pamplona Alta in Lima and (iv) Mukuru in Nairobi. Their layouts are given in Figure 2.

Several criteria were used to identify these neighbourhoods. First, they are all primarily formed of low-income urban settlements with poor sanitation provision. Second, Fosen Michel, Pamplona Alta and Mukuru all have an existing CBS service provided by different social enterprises (SOIL, x-runner and Sanergy, respectively) who are looking to expand their service in the most efficient way possible. CBS is also provided in BM Section, but from

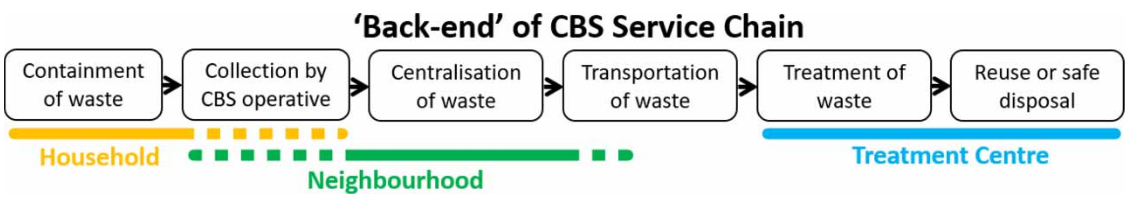

Figure 1 | Components of the 'back-end' CBS service chain (with the spatial context of each).

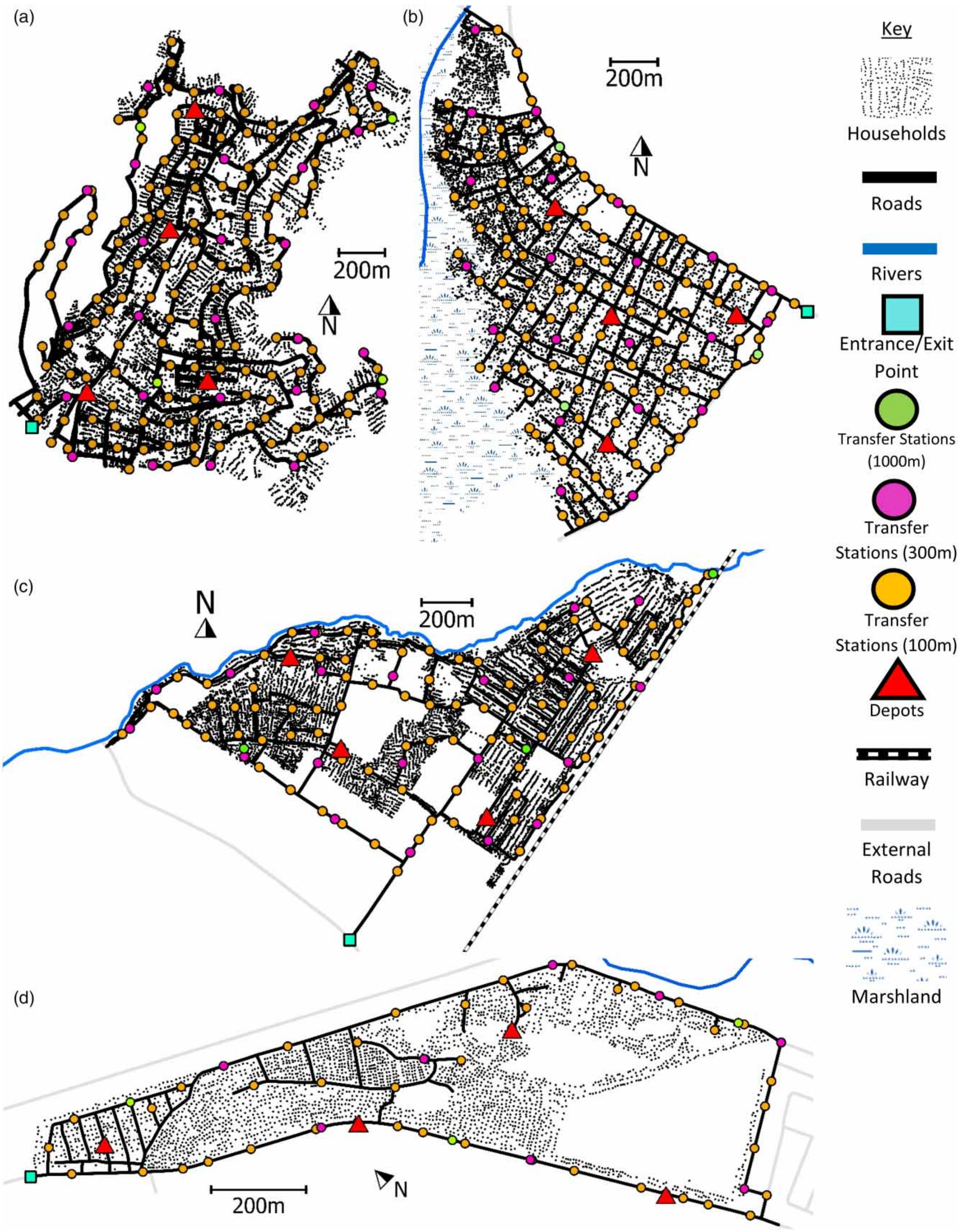

Figure 2 | Maps showing the study areas within the neighbourhoods of (a) Pamplona Alta, Lima, (b) Fosen Michel, Cap-Haïtien, (c) Mukuru, Nairobi and (d) BM Section, Cape Town. The entrance/exit points, transfer stations and depots are hypothetical (see the 'Model construction' section).

the local City of Cape Town municipality. Third, there are identifiable geographical features giving a clear definition of neighbourhood boundaries. For example, Fosen Michel is on a spur of land between the Rivière Mapou and the coast, while Pamplona Alta fills a single steep-sided valley. Likewise, Mukuru lies between the Ngong river and a railway line. BM Section is located within the Khayelitsha Township and is bounded by Govan Mbeki Road, R2 national highway and the Kuils River. Apart from Pamplona Alta, the neighbourhoods lie in flat basins with little topographical variation.

Strategy characterisation

A CBS provision strategy is defined as the mechanism by which organisations providing a CBS service choose to navigate a neighbourhood to visit their customers and ensure a safely managed sanitation service. Any strategy is typically based on a combination of mechanised and pedestrian journeys. Through liaison with different CBS organisations, three separate strategies were identified for evaluation as part of this research. These will be described here.

1. *Strategy A*: This is based on an approach that has been used by SOIL in Fosen Michel. CBS collectors enter a neighbourhood with a mechanised collection vehicle, before taking the shortest route along the road network to the closest point to a CBS household. The housing density of neighbourhoods using CBS typically results in limited road access. The CBS operator then walks to the CBS user's household or compound and collects the filled CBS container (simultaneously dropping off a clean one). The CBS collector returns to the collection vehicle to deposit this waste and drive onwards. This process continues until all CBS users have been visited, whereupon the collection vehicle exits the neighbourhood and returns to a treatment site.
2. *Strategy B*: This is informed by Sanergy's approach in Mukuru and is very similar to Strategy A, except in this case all collection operations are based out of a neighbourhood depot. A household service is offered in the same way, but collection routes all begin and end at the depot. Collated waste is then removed for treatment by a separate transport process. A key variable for this strategy is the location of the depot within the neighbourhood.
3. *Strategy C*: This is based on an approach used by Sanima in Pamplona Alta. All CBS users walk with their own filled containers from their households to the nearest transfer station (in reality, these locations can range from being a layby to a container 'vending machine'). In practice, CBS users have been known to produce 1.12 kg of faecal waste per user per week (Tilmans *et al.* 2015). Having entered the neighbourhood with mechanised collection vehicles, CBS collection operatives meet users at these points and exchange filled containers for fresh ones. Users return home with fresh containers, while CBS operatives move to the next transfer station. The implications of users carrying filled containers over these distances are discussed in the 'Discussion' section. A key variable for this strategy is the number (or spatial density) of transfer stations across a neighbourhood.

The routing efficiencies of each of these strategies will vary with the number of CBS users being served. Therefore, each was evaluated with 10, 20, 30, 50, 70, 100, 250, 500, 1,000, 3,000 and 5,000 CBS users in each neighbourhood.

Unless otherwise stated, all strategies will assume a capacity of the collection vehicle of 50 CBS containers – this is the approximate capacity of a converted tuk-tuk (which are commonly used for this purpose).

Model construction

To ensure a robust examination, all characterisations of CBS provision strategies must be informed and applied in a uniform manner across the four locations. In these locations, as in many areas where CBS might be considered most appropriate (i.e. low-income urban environments), there is typically limited spatial data for informing neighbourhood topology. Moreover, any methodology developed as part of this research will be most useful to organisations looking to apply it in such contexts. Therefore, adopting a minimal data approach and using open-source tools were deemed pragmatic methodological decisions (and has precedent in work carried out in similar environments (Schoebitz *et al.* 2017; Grippa *et al.* 2018)). The limitations of this approach are highlighted in the 'Discussion' section.

As such, each neighbourhood domain was characterised by only: (i) a primary road network and (ii) the location of household structures within the area. The road network was obtained from Open Street Map (OSM). The location of buildings was identified using point clouds (i.e. one point per structure) inferred from visual inspection of building footprints using ESRI's World Imagery (Clarity) layer[1].

Hypothetical sets of CBS users within each neighbourhood were created through random sampling of the building point clouds. The smaller the number of users, the greater the spatial variance between each set (e.g. the spatial variance between two sets of 10 users was higher than two sets of 1,000 users). To mitigate the

[1] (https://www.arcgis.com/home/item.html?id=ab399b847323487dba26809bf11ea91a).

influence of this, multiple sets were used at each level of CBS usage, with 50 random sets for usage up to 100 CBS users; 25 sets for 250 and 500 users; and 10 sets when users were 1,000 or more.

Each road layout informed a network model. These networks were built with NetworkX (an established Python network analysis package) (Hagberg *et al.* 2008) with roads represented as edges. As shown in Figure 3, the nodes in these networks were stopping points, transfer stations and depots (depending on the strategy being evaluated). In each case, an implementation of the weighted Dijkstra algorithm (Dijkstra 1959) was then used to construct a distance matrix, **M**. This is a square matrix (symmetric around the lead diagonal) where $\mathbf{M}_{ij}$ is the distance between nodes i and j (rounded to the nearest integer).

All three strategies were optimised as 'capacitated vehicle routing problems' (CVRPs; Ralphs *et al.* 2003) using the Operational Research tools suite from Google (Google-OR Tools)[2]. Google-OR Tools is an open-source software suite with an established heuristic solver for route optimisation problems (Zhang *et al.* 2020; Zhao *et al.* 2020). The representation of each strategy within this framework will now be briefly described (Python scripts for each are given in the additional information).

1. *Strategy A*: All stopping points (i.e. points on the road network closest to the CBS user) were represented as nodes in the network (and a row within matrix **M**).
2. *Strategy B*: The depot node was the start and finish point for the network. To understand how routing efficiencies might rely on the location of this depot, four hypothetical locations were evaluated for each neighbourhood, with approximately one in each quadrant of each neighbourhood (see Figure 2 for their placement).
3. *Strategy C*: Each transfer station represented a node on the network graph (and a row in matrix **M**). Each node had a load characteristic, equal to the sum of the CBS users using that transfer station. In order to fully understand the impacts of this transfer station model, different densities of transfer station have been evaluated in each neighbourhood. Hypothetical transfer stations are either approximately 100, 200, 300, 500 and 1,000 m apart (see Figure 2).

Broadly, in each case, the solver attempts to minimise the longest route in the series journeys required to visit all nodes in the graph when vehicles have a limited capacity. This research uses the default solver with the first solution obtained with a *path-cheapest-arc* approach (i.e. iteratively extending the route to the closest node) and the commonly used 'guided local' search method, which avoids producing routes that are shorter than all those nearby but not the global minimum. Solutions were found using Cranfield University's Delta High Performance Computing cluster with a single chunk of 16 CPUs, each with a minimum 8 GB of memory (and 16 parallel message passing interface processes). In each case, the solver had a limit of 300 s.

By providing the total driving distance required, the optimisation exercise provides one of the two key metrics used in evaluating the CBS strategies. The other metric is the total walking distance required (by either the CBS

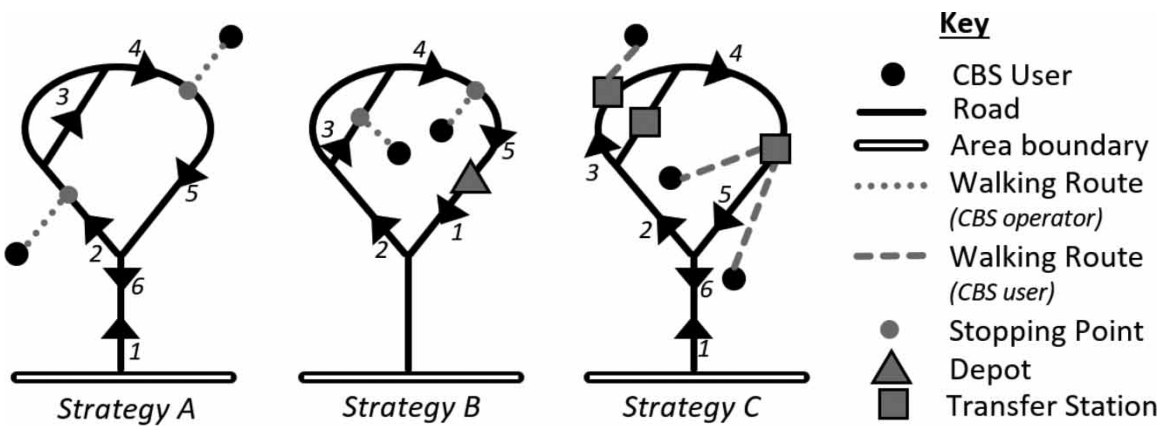

Figure 3 | A conceptual example of each CBS provision strategy (with numbered arrows indicating mechanised routes).

[2] https://developers.google.com/optimization/).

collector or the CBS users) for the strategy to function. This research assumes that all pedestrian journeys are the shortest linear path between two points. The appropriateness of this assumption has been discussed in a variety of WASH contexts (Ho *et al*. 2014; Nygren *et al.* 2016), but because of a lack of data on paths and access routes within these low-income urban settlements, this was deemed a pragmatic methodological decision.

RESULTS

Results for Strategy A

Figure 4(a) and 4(b) demonstrates how the requisite driving and walking distances under Strategy A evolve as the number of CBS users increase across the four case study neighbourhoods. These walking and driving distances are all completed by CBS employees (see the 'Model construction' section for a description of Strategy A). It should be noted that the BM Section plot is limited to 3,000 users by the structures identified from satellite imagery (see the 'Model construction' section).

Figure 4(a) illustrates Pamplona Alta has highest driving distances, followed by those for Fosen Michel and Mukuru (which are very similar) and then the BM Section (which are significantly smaller). A capacity of 50 CBS units is reflective of a tuk-tuk (a three-wheel vehicle often used in neighbourhood CBS collection), although this would be context-specific. As the capacity of the collection vehicle increases, the relative order of the four neighbourhoods remains the same, although the overall distance magnitudes are much smaller.

Figure 4(b) illustrates how the total walking distance rises with increased CBS usage. The linearity of these plots is driven by the uniformly random spread of hypothetical CBS users across each neighbourhood. Here, the differences between the neighbourhoods are much smaller (Pamplona Alta and Mukuru are nearly identical as the number of users increases).

Together, the two figures give an informative measure on the accessibility of each neighbourhood. For example, BM Section's lower driving distances coupled with higher walking distances results from both (i) the smaller neighbourhood area and (ii) the lack of penetrative road infrastructure (see Figure 2). On the other hand, Pamplona Alta has the highest driving distances, but its walking distances are similar to Fosen Michel and Mukuru. Again, this is because of two compounding factors. The first is the slightly larger neighbourhood area. The second is the serpentine road network (necessitated by local topography) which inhibits the ability of collection vehicles to traverse the neighbourhood.

Results for Strategy B

Figure 5 presents the results for Strategy B (with collection vehicles having a capacity of 50 CBS units). The figure gives an envelope for each neighbourhood which covers the extent of four separate curves (one for each of the hypothetical depots shown in Figure 2). Therefore, each neighbourhood's envelope demonstrates the range in required travel distance for different depot locations.

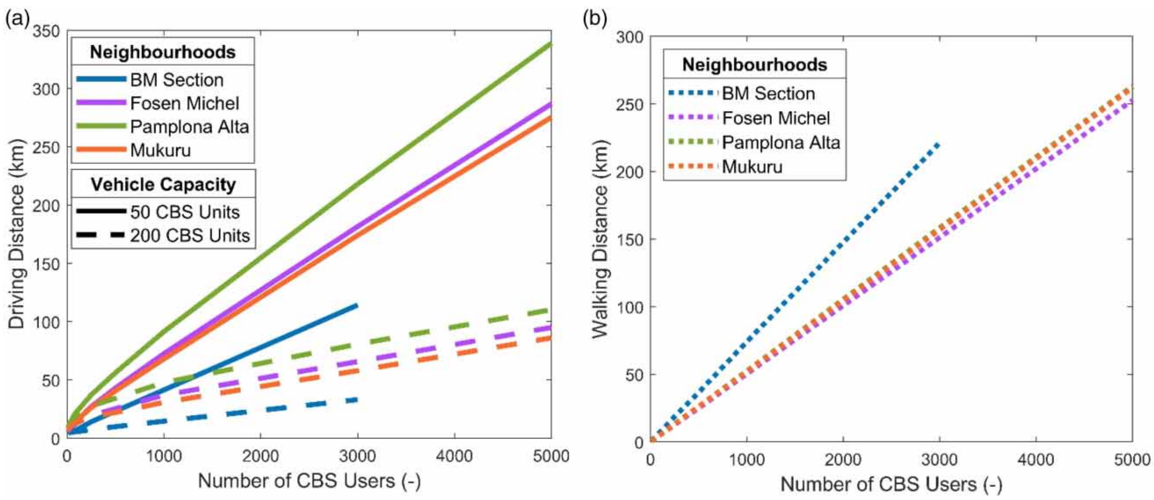

Figure 4 | Comparing the total driving and walking distances required by Strategy A to serve all four case study locations.

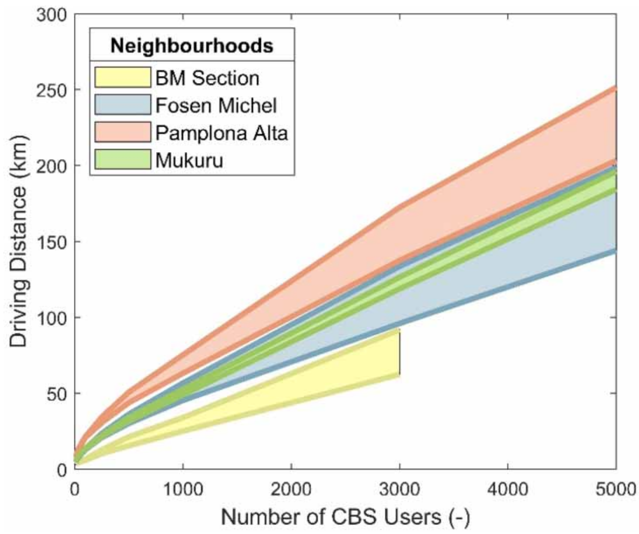

Figure 5 | Comparing increased CBS usage with the range in driving distances required to implement Strategy B.

The four envelopes follow the same shapes seen in Figure 4(a) for Strategy A, with Pamplona Alta consistently producing the longest distances and BM Section the smallest. However, across all four neighbourhoods, the envelopes give shorter distances than those seen for Strategy A. While this suggests that a CBS provision strategy with an internal depot improves efficiencies, it should be recognised that this model does not account for the removal of waste from the neighbourhood (as this is dependent on the CBS provider's trucking availability).

In all four areas, the range in optimised travel distance increases with the number of hypothetical CBS users. This indicates that the location of a provider's depot becomes increasingly important as the number of users increase. Figure 5 suggests that, when there are 3,000 users in the BM Section neighbourhood, the location of depot can reduce total travelling distance by over 30%. However, there are also differences in the envelopes' spread, suggesting that the road network influences how important depot location can become. As a result, the figure suggests that the location of a depot is more important in Fosen Michel than it is in Mukuru. This could be because of the denser road network (see Figure 2) allowing greater variation in neighbourhood routes. However, it is worth noting that the variation seen for the small BM Section (with the lowest road density) remains relatively large. It is hypothesised that this is because the elongated neighbourhood shape makes the most southerly depot particularly inefficient.

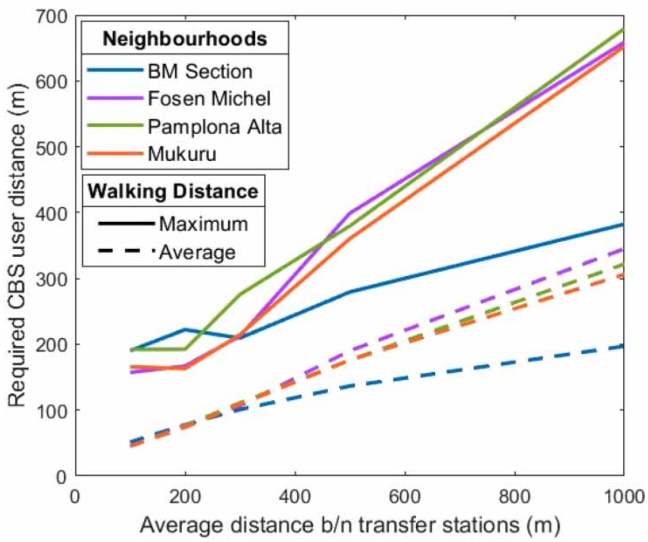

Figure 6 | Comparing the evolution in average and maximum walking distances for CBS users necessitated by Strategy C as transfer stations become more sparse.

Results for Strategy C

Figures 6 and 7 give the results for Strategy C.

Figure 6 illustrates how the average and maximum walking distances (for all potential users identified in the four neighbourhoods) evolve as transfer station density reduces. As one would expect, the average distance rises steadily as the distance between transfer stations increases. With the stations approximately 1,000 m apart (which equates to three transfer stations in each neighbourhood), the average walking distance can range between 180 m (in BM Section) and 320 m (in Fosen Michel) – the implications of this are discussed later in the 'Discussion' section.

Intriguingly, the maximum walking distances in all four neighbourhoods inflect as the distance between stations rises. This suggests that there is a transfer station density that optimises the balance between (i) the number of stations required and (ii) the furthest a CBS user needs to travel with a full CBS container. For Fosen Michel, Pamplona Alta and Mukuru, Figure 6 suggests that this occurs when the stations are approximately 200 m apart. For the BM Section, this distance is 300 m. It is also worth noting that the BM Section has the highest maximum walking distance (of the four neighbourhoods) when transfer stations are 100 m apart, yet the lowest maximum when they are 1,000 m apart. This reiterates how the density and layout of the road network is critical in determining efficiency of CBS provision strategies.

Figure 7 compares the average distance between transfer stations with the required collection driving distance for different levels of CBS usage. The figure demonstrates that reducing the density of transfer stations has varying effects across the different neighbourhoods. Broadly, driving distances do not necessarily correlate with density of transfer stations.

For example, Figure 7(a) indicates that the driving distances in the BM Section typically increase when transfer stations go from being 100–200 m apart (i.e. when the number of stations in the neighbourhood reduces). It is hypothesised that the single road circuit serving the southern half of the neighbourhood homogenises routes. This, coupled with the slightly longer gap between stations, increases the requisite distances. However, these

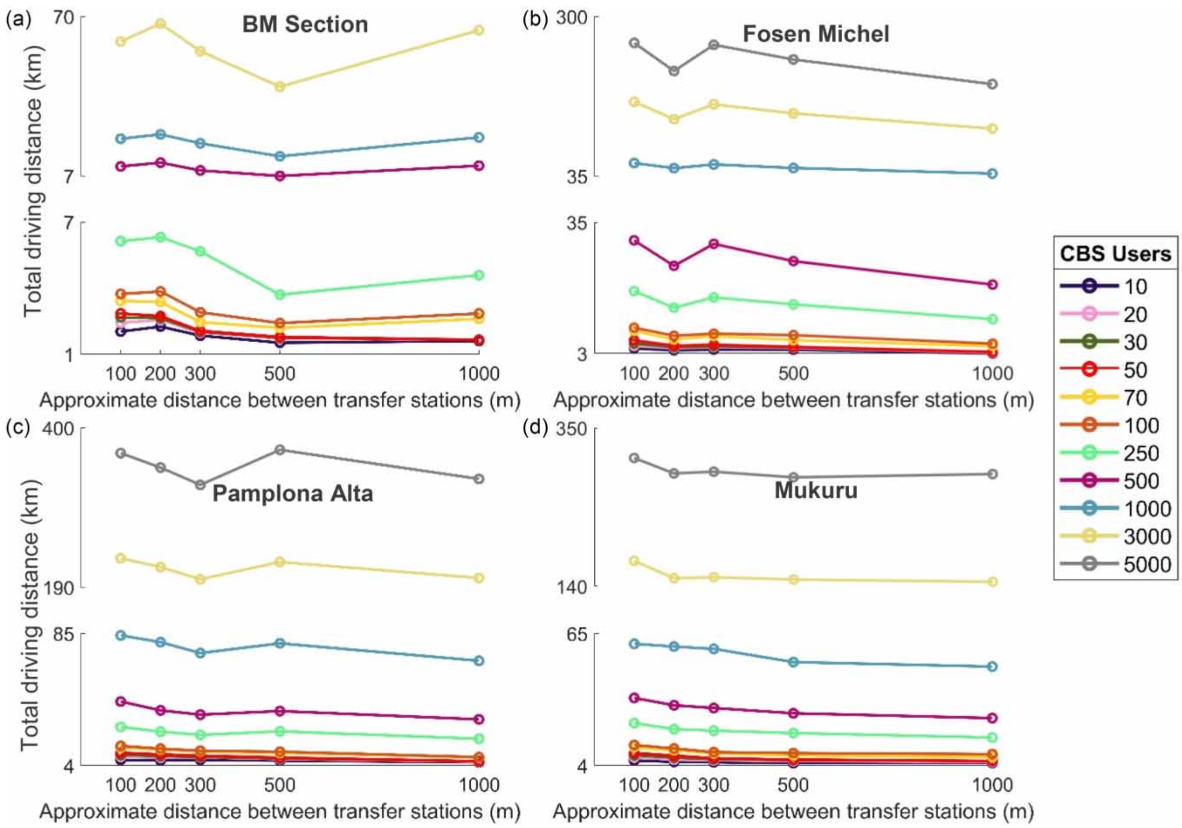

Figure 7 | Comparing the distance between transfer stations and the consequent driving distance required to serve varying numbers of CBS users in (a) BM Section, (b) Fosen Michel, (c) Pamplona Alta and (d) Mukuru. (Note: the split y-axes are all linear, this is to aid clarity of the relationships for different numbers of CBS users).

reduce as transfer station spacing increases further to 300 and 500 m. This is because the reduced station density now means that the southerly road circuit is not being circumnavigated as frequently. Interestingly, travel distances increase again as the station spacing increases further. This results from the necessary repeat visits to the three transfer stations, two of which are in the southerly end of the neighbourhood (furthest from the exit).

In the other neighbourhoods, this evolution in required driving distance (as transfer station spacing increases) is different. In Fosen Michel, there appears to be an 'optimal' transfer station spacing of 200 m. It is hypothesised that this occurs because this station density offers the best balance between (i) minimising the intricacy of routes around the dense road network (which occurs with lower spacing) and (ii) minimising the need for repeat trips (which occurs with higher spacing). From 300 m upwards, Fosen Michel sees a steady decline in the required driving distances.

In Pamplona Alta, there appears to be a similar 'optimal' transfer station density at 300 m. It is conjectured that this is higher because of the more convoluted road network. It is interesting to note that, particularly at higher rates of CBS usage, there is little difference in driving distance when transfer stations are 100 or 500 m apart. In Mukuru, there appears to be no 'optimal point', possibly because road density varies significantly across the neighbourhood.

More broadly, it can be seen that the relationships shown in Figure 7 all become more acute as usage increases (in other words, optimal transfer station densities have a greater impact when there are more CBS users). However, it should also be recognised that, across all four neighbourhoods, there is not a substantial reduction in requisite driving distances as transfer station spacing increases from 100 to 1,000 m. This highlights a crucial limiting factor – the capacity of the collection vehicle. The small collection capacity assumed here (approximately that of a tuk-tuk) means that many repeat trips are needed to serve individual transfer stations. This diminishes the routing efficiencies one might expect from a more 'centralised' approach to CBS service provision (i.e. having fewer stations). The implications of these observations are discussed in the 'Discussion' section.

Finally, it should be noted that, at certain levels of CBS usage and station density, this strategy encounters a problem around transfer station 'demand stacking'. In other words, the number of CBS containers at a single transfer station fills the majority of a collection vehicle's capacity. The routing solver does not allow for the remaining capacity to be filled by a fraction of the units at another station. Therefore, the model sees a higher proportion of vehicles exiting the neighbourhood without their load nearing capacity (and in some cases, this prevents a solution). This phenomenon affects all four neighbourhoods when there are 500 hypothetical users (at higher numbers, the need for return trips mitigates the issue). Therefore, a pragmatic methodological decision was required – for the affected scenarios (i.e. 500 users for Strategy C across all neighbourhoods), the overall collection capacity was expanded by 20% through additional vehicle trips. In practice, this problem could be mitigated by collection vehicles being filled by partial loads at other transfer stations (although this could become a complex organisational problem). This would be a real-world issue for a transfer station provision strategy as CBS goes to scale.

Comparison of strategies

It is also important to understand the statistical significance of the comparative differences between the three strategies as CBS usage increases. To do this, several different statistical metrics have been employed to evaluate the sets of scenario (as described in the 'Model construction' section).

In all four locations, Strategy B consistently produces lower driving distances than those for Strategy A. This can be demonstrated using a series of independent two-tailed *t*-tests to compare the arithmetic means from Strategies A and B. With 70 users, Strategy B produces statistically significant (i.e. $P < 0.05$) smaller driving distances of over 3.6% in BM Section ($t = 4.8$, $df = 98$, $P < 0.01$), 7.5% in Fosen Michel ($t = 9.9$, $df = 98$, $P < 0.01$), 4.1% in Pamplona Alta ($t = 4.1$, $df = 98$, $P < 0.01$) and 11.8% in Mukuru ($t = 10.1$, $df = 98$, $P < 0.01$). With 3,000 CBS users, Strategy B produces even greater improvements over Strategy A, with the statistically significant differences rising to 11.8% (t-stat $= 36.5$, $df = 18$, $P < 0.01$), 19.2% (t-stat $= 83.2$, $df = 18$, $P < 0.01$), 13.1% (t-stat $= 26.4$, $df = 18$, $P < 0.01$) and 20.2% (t-stat $= 58.7$, $df = 18$, $P < 0.01$), respectively. The *t*-stats are much higher for the 3,000 user sets, highlighting the greater differences between Strategies A and B at higher CBS usage. Various Analysis of Various (ANOVA) tests were also used to understand the significance of the various locations of depot under Strategy B (and observations made on Figure 5). The resultant P values decreased from between 0.08 and 0.76 for 10 users (the range is across the four locations) to under 0.0002 for 100 users and less than 0.0001 for 3,000 users. This demonstrates the increasing statistical significance of the depot location as the number of users increases. It should be noted, however, that the distance required to transfer CBS units from the depot out of the neighbourhood and onwards to a treatment site has not been considered here.

When comparing Strategy C and Strategy A, the picture is a little more complex. This is partly because they put different burdens on the CBS provider and the CBS user. While Strategy A is a household service, Figure 6 details how Strategy C puts burden on CBS users by requiring they walk with a container filled with waste to a transfer station. Given the random spatial spread of CBS users across the multiple sets (see the 'Model Construction' section), the walking distances are normally distributed. Therefore, when transfer stations are 100 m apart in each of the four locations, approximately 84% of CBS users would have to carry their waste more than 20 m. However, only 2% of users will need to carry their waste more than 89 m (this value is 114 m in BM section because of the sparse road network). Conversely, when stations are 1,000 m apart in Fosen Michel, approximately 98% of CBS users will need to carry their waste more than 92 m (compared with 60 m in Nairobi and 29 m in BM Section). Any burden of this type could have implications on the accessibility of such a provision strategy – there is wide recognition that sanitation systems in low-income environments can discriminate unfairly based on gender (Stevenson *et al.* 2012; Sommer *et al.* 2014; Chandra *et al.* 2015) or disability (Wrisdale *et al.* 2017; Mactaggart *et al.* 2018). Furthermore, such strategies may raise questions around the comfort and dignity afforded to CBS users. These issues are of critical importance and would need appropriate consideration before implementation of a CBS provision strategy based on transfer stations.

However, Strategy C generally produces shorter driving distances than Strategy A – particularly up to 250 CBS users. Given the non-normal distributions involved, the Mann–Whitney test (a non-parametric alternative of the independent *t*-test) was used to establish statistical significance between the arithmetic means for both strategies. With 100 users in the BM Section, the difference was 48% ($U = 68$, $n_1 = n_2 = 50$, $P < 0.01$) with a 100 m transfer spacing and 60% ($U = 200$, $n_1 = n_2 = 50$, $P < 0.01$) with a 1,000 m spacing. With 100 users in Pamplona Alta, the difference was 30% ($U = 0$, $n_1 = n_2 = 50$, $P < 0.01$) with a 100 m transfer spacing and 60% ($U = 0$, $n_1 = n_2 = 50$, $P < 0.01$) with a 1,000 m spacing. Fosen Michel and Mukuru saw similar trends at 100 users (see additional information for full data). With 3,000 users in BM Section, the difference between Strategies A and C reduces slightly – although Strategy C remains at least 43% ($U = 0$, $n_1 = n_2 = 10$, $P < 0.01$) shorter. This trend is also seen in Fosen Michel, with 5,000 users being served by transfer stations 100 m only being 11% ($U = 0$, $n_1 = n_2 = 10$, $P < 0.01$) shorter than providing a household service. In fact, the equivalent scenario in Pamplona Alta and Mukuru (i.e. 5,000 users, 100 m station spacing) leads to greater distances than providing a household service – by 9.5% ($U = 0$, $n_1 = n_2 = 10$, $P < 0.01$) and 12.6% ($U = 0$, $n_1 = n_2 = 10$, $P < 0.01$) respectively. This is caused by repeat trips to transfer stations and highlights the importance of their location, particularly with lower station spacing and higher CBS usage (reinforcing the findings of Kennedy-Walker *et al.* (2014)).

DISCUSSION

The results presented in the 'Results' section have broader implication for CBS and road-based FSM provision strategies.

For example, the results across all three strategies emphasise the dependency of CBS provision on the capacity of the collection vehicles. Figures 4(a) and 5 demonstrate that, with a collection capacity of 50 (approximately that of a tuk-tuk), there appears to be limited benefit from economies of scale (in terms of routing distances) with the different household provision strategies. Similarly, even when neighbourhoods were sparsely served by transfer stations, the results demonstrate that the number of return trips make reductions in driving distance minimal (although, as Russel *et al.* (2015) highlighted, such a strategy may well cause users shame associated with the self-transfer of waste). Other strategy metrics, such as time taken or scheduling, could offer an alternative viewpoint on service characteristics. Another key consideration would be a strategy's potential health impacts on users and CBS operatives (Bischel *et al.* 2019). Despite this, the results here suggest that economies of scale in the requisite routing for CBS provision will be largely conditional on greater collection capacity (rather than any particular provision strategy). However, it is worth noting that this study has focused on a component of the whole CBS service chain (see Figure 2) and there may well be other economies of scale in other processes.

Increasing collection capacity will require larger vehicles to navigate urban informal settlements, areas that are typically characterised by a dense urban fabric with narrow access routes that evolve with time (Hassan 2012; Jones 2019). This raises questions about the ability of CBS provision strategies to scale efficiently without appropriate road access and reflects longstanding concerns about off-grid sanitation more generally (Henry Yongsheng

& Jun 2006; Foppen & Kansiime 2009). While limited accessibility to a settlement may be an argument for CBS, such conditions also constrain the ability of the service to scale efficiently. Furthermore, while improving accessibility may improve CBS scaling potential, it could then become more appropriate to deliver an alternative form of sanitation such as high-quality on-site latrines or septic tanks.

The introduced methodology does allow for further evaluation on this problem of access. In evaluating Strategy B, four hypothetical depot locations were evaluated for each neighbourhood. Figure 5 demonstrates how the different locations influence the total driving distance necessary to serve all households. Figure 8 demonstrates how Depots 1, 2 and 3 influence the roads used in Fosen Michel when there are 100 CBS users spread across the neighbourhood. As might be expected, the figure illustrates the high usage around the northern areas which have less road infrastructure (so repeat journeys to serve users are more frequent). Interestingly however, Figure 8 also shows large similarities in road usage across the four depots. Those routes offering the shortest distance between different areas of the neighbourhood see much heavier use. This observation has several implications.

First, it highlights an inherent fragility of road-based FSM systems. If one of these frequently used routes were to be blocked (for example, by flooding or development), there would be a disproportionate effect on the efficiency of the CBS provision service. Second, ensuring viability of CBS at scale will be dependent on both (i) the location of service infrastructure (depots, transfer stations, etc.) and (ii) maintaining access through key routes within a neighbourhood. Interestingly, this raises the possibility of treating access around road-based FSM as analogous to that of flow around traditional, sewered sanitation systems. There is extensive literature on the statistical prediction (and consequence) of conveyance degradation through traditional sewer networks (Mohammadi *et al.* 2019; Dong *et al.* 2020). If CBS is to scale up, similar methods may be necessary to understand the impact of fluctuations in road access. While this research paper introduces a methodology (scripts given in supporting DOI) by which the criticality of different routes can be identified, evaluating consequences of failure is beyond its scope. Separately, results such as those in Figure 8 could raise interesting arguments around efficiency of road-based FSM and 'reblocking' (i.e. the clearance of land to change the topology of a neighbourhood), which in recent years has become increasingly common, if contentious, urban planning strategy for low-income environments (Brelsford *et al.* 2018; Brelsford Martin & Bettencourt 2019; Kiefer & Ranganathan 2020).

Finally, it is worth recognising that this research has developed a methodology bounded by a neighbourhood's extents. However, typical CBS service chains (see Figure 2) typically necessitate filled waste containers to be transported to an external treatment centre (this is the case in all four neighbourhoods studied here). While service efficiencies within the neighbourhood remain important, they could be overshadowed by this process if a treatment centre is well beyond city limits. Investigating this problem would require a wider methodological scope and could be an interesting area for further study.

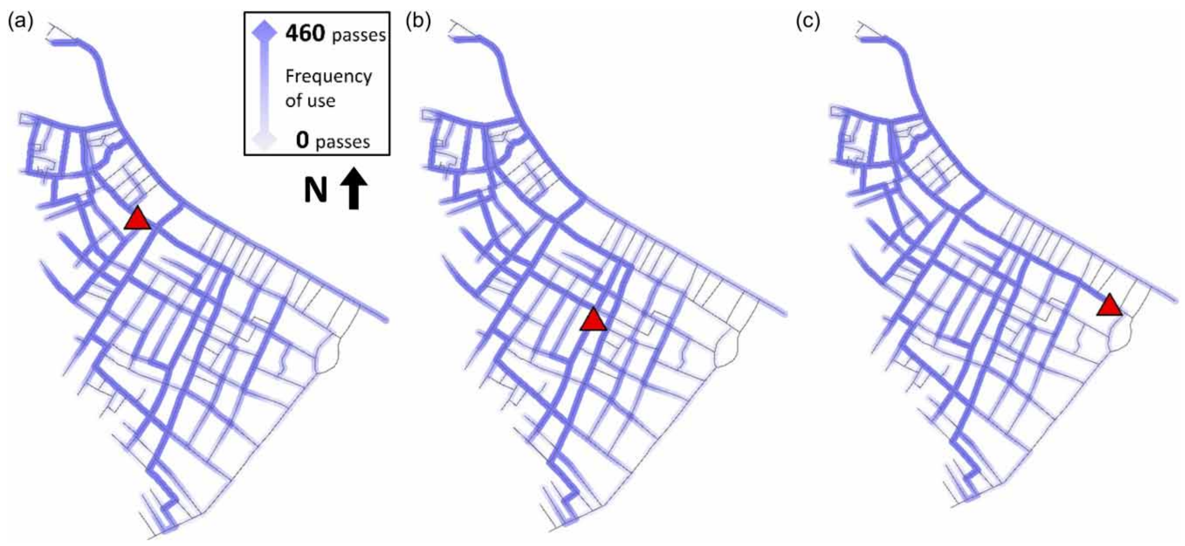

Figure 8 | Demonstrating the spread of road usage by collection vehicles (for 100 CBS users) when based out of (a) Depot 1, (b) Depot 2 and (c) Depot 3.

Limitations of methodology

The methodology presented here relies on a hypothetical scenario basis to inform wider discussion about the efficiencies of CBS provision strategies. While the strategies are based on practical examples, the feasibility of scenarios (placement of transfer stations, depots, etc.) being physically implemented was beyond the scope of this research paper.

However, several methodological decisions should be acknowledged for their potential impact on the results. Firstly, the model relies on OSM for the road network. The limited accuracy of OSM road networks in such environments has been highlighted in the literature (Bakibinga *et al.* 2019), with access potentially evolving over time or with season. For instance, it is known that a northern area of Fosen Michel was demolished in late 2020 (there is no data available yet on access changes). However, there remains strong precedent for using OSM for low-income and unplanned urban environments (Biswas *et al.* 2018; Branchet *et al.* 2019). Similar limitations exist for the representation of the buildings (which were manually identified from satellite imagery), compounded by the fact that the method cannot account for the different functions of each structure (household, business, storage, etc.) or those with multiple storeys. However, the neighbourhood point clouds give a reasonable representation of building density within a neighbourhood and given the absence of other data, this approach was deemed a pragmatic methodological decision.

Secondly, the model has assumed the neighbourhood to be a flat plane, with efficiency determined solely by distance travelled. This is a reasonable approximation in BM Section, Fosen Michel and Mukuru. However, parts of Pamplona Alta sit on very steep slopes, which will influence efficiencies of vehicles moving around the neighbourhood. Alongside this, steep slopes make assuming the shortest linear distance as the walking route unrealistic (access in Pamplona Alta often relies on informal stairways). However, the purpose of this work is to demonstrate the use of an open-source method (requiring minimal data input) for evaluating the efficiencies of different CBS provision strategies and incorporating topographical effects into the underlying distance matrices adds significant complexity and computational requirement.

Finally, the strategies have been evaluated on a single metric – the requisite travel distance (on foot and by vehicle). This has precedent in other route optimisation exercises for FSM (Kennedy-Walker *et al.* 2014). However, another metric (such as time or topographical height gain) may yield different conclusions. For instance, strategies using sparser transfer stations will reduce 'start-stopping' delays and therefore might take less time and use less fuel, despite overall travel distances being higher. Furthermore, a time-based evaluation could bring in consideration of different filling rates for containers, which could mean CBS users not all needing the same frequency of servicing. This study has not considered the viability of the infrastructure needed to support each CBS provision strategy (e.g. depots, transfer stations, etc.). The installation of infrastructure for urban sanitation in impoverished areas has been known to be problematic (Holm *et al.* 2021). Any installation is likely to be driven by land availability rather than resultant routing efficiencies – as discussed in Bosompem *et al.* (2016) for the installation of transfer stations in Kumasi. These various other evaluation metrics (along with full cost–benefit analyses) is an area for further work (Russel *et al.* 2019), possibly using costing data from the 'Climate and Costs in Urban Sanitation' project (Sainati *et al.* 2020).

CONCLUSION

This research paper has introduced a methodology using an open-source routing solver within a minimal data requirement for evaluating the routing efficiencies of different CBS provision strategies. Using a hypothetical scenario-based approach, three separate strategies were shown to have varying efficiencies at different levels of CBS usage in neighbourhoods in Cape Town, Cap-Haïtien, Lima and Nairobi. This approach, while providing insight into the efficiencies of different existing CBS provision strategies, should be properly contextualised by recognising the wide range of factors that determine the sustainability of any sanitation service (Bhagwan *et al.* 2019).

A household-based service (named Strategy A) was shown, in the main, to require the largest travel distances by the CBS collection vehicles. Having a depot within the neighbourhood reduces these distances. As CBS users increased, the location of this depot become increasingly important to a greater (e.g. Fosen Michel and BM Section) and lesser (e.g. Mukuru) degree. Provision strategies using transfer stations were also evaluated. These had the greatest routing efficiencies at low CBS usage. However, with greater numbers of users, more repeat trips to individual transfer stations were necessary, which meant less benefit from this more centralised approach.

More broadly, the modelling highlights several key considerations with regards to the routing necessary for delivering CBS at scale. First, no single CBS provision strategy offers a universal solution, as there is clear dependency on the road layout within the served community. Second, routing efficiencies of any particular strategy evolve with the number of people using the service. Third, the results illustrate the importance of increased collection vehicle capacity in achieving operational economies as CBS usage scales-up. This underscores the need for reliable road access around low-income urban environments where road-based approaches are being considered as long-term solutions for sanitation provision. In linking the viability of a scaled CBS service with the characteristics of a neighbourhood's road network, this paper highlights the importance for integrated urban planning to better incorporate sanitation provision.

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ADDITIONAL INFORMATION

The scripts used for pre-processing and each CBS strategy, spatial data (location of depots, transfer stations, buildings) and primary results are given at the following: https://doi.org/10.17862/cranfield.rd.14495961

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (https://doi.org/10.17862/cranfield.rd.14495961.v1).

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