FROM TRASH TO DIGITAL TREASURE: URBAN DIGITAL TWINING FOR SOLID WASTE MANAGEMENT

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Enschede, The Netherlands, August 2023

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A CASE STUDY IN THE CITY OF TSHWANE, SOUTH AFRICA

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ABSTRACT

Urban sustainability faces a critical challenge in managing solid waste. With over 2 billion metric tons generated annually, global waste production has severe health and environmental consequences. Though not a primary SDG, effective waste management is vital for meeting targets 11.6, 12.4, and 12.5 and is intertwined with 12 out of 17 SDGs. South Africa, in particular, grapples with significant waste generation and inadequate collection services. A dynamic model is proposed to tackle these issues, integrating real-time monitoring, optimized collection routes, and citizen participation. This study introduces a prototype for a Waste Management Digital Twin, involving stakeholder prioritization, citizen engagement via an open-source tool (Epicollect5) for locating waste containers and littering sites, waste generation simulations, optimized collection routes, and a control dashboard. A three-day data collection effort identified 1,270 containers and 820 littering sites, revealing container distribution gaps. Litter in park areas emphasizes the importance of providing well-distributed containers and prompt maintenance. Photos aid issue identification, while citizen engagement improves accuracy and efficiency. Waste generation simulations inform waste flows, low-capacity areas, and optimal container locations. Optimized collection routes are proposed to reduce fuel use and emissions. A control dashboard was developed where stakeholders' system requirements were included, and eleven indicators were displayed along three maps. Stakeholders rated the dashboard high, but some did not perceive the overall objective of digital twinning solid waste. Performance of the Digital Twin depends on computer capacity and local or online processing. The prototype sets the foundation for digital twinning in waste management, scalable to different areas, vehicles, and production levels. Digital twinning, citizen involvement, and multi-stakeholder engagement enhance waste management, particularly benefiting resource-limited countries.

Key Words:

Digital Twins, Solid Waste Management, Citizen Science, Volunteered geographic information, VRP

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I always had many ideas for testing scenarios, but deciding and focusing on one was challenging during this Master's. I jumped from data visualization to migration to war emotional effects, climate change emotions, solastalgia, and solid waste in South Africa. I was lucky to have many people around to help me navigate all these ideas and the challenges that were arising daily.

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Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

The term urban digital twin refers to a digital replica of some of the physical assets of a district or neighborhood of a city that can be used to co-create and test scenarios with city-specific parameters (Ruohomaki et al., 2018). It goes beyond the static 2D or 3D representation, becoming a model for the past, present, and future state (Digital Twin Geohub, 2022). Digital twinning aims to provide laboratory mechanisms for understanding the spatial dynamics and the impacts of climate change, biodiversity loss, permeability, unsustainable transport, and effects of anthropogenic impacts on the city environment (Caprari, 2022). An urban digital twin falls within the Augmented Urban Planning framework for strategic planning (Azadi et al., 2023) and can work as a Decision Support System to inform urban planners and designers of the impact a project development will have and be a driver for citizen involvement in the planning process (Dembski et al., 2019, 2020; Maciej Serda et al., 2019).

Urban digital twins can be confused with smart cities as the concepts are related. However, digital twins build on the smart city model as another layer where the data collected with smart city-level sensors can be used for simulations, analysis, and decision-making (White et al., 2021). These decisions are then returned to the physical world as implementations that modify the city and update the underlying layers the smart city is built on (ibidem). It turns the process into a data feeding - information response – implementation reaction cycle that can move in near-real time and can operate as Urban Computing workflows based on web communication and processing (Nourian et al., 2018). In the first step of feeding data in the cycle, cities are turning to the use of the Internet of Things – IoT for data collection (Peralta Abadía et al., 2022)using sensors that communicate through technologies such as Wi-Fi, mobile networks - 3G/4G/5G-, 6LoWAN, Bluetooth, Radio or NFC (Balaji et al., 2019) to address challenges such as air quality (Mak & Lam, 2021), traffic management (Ibrahim et al., 2022), parking occupancy, or parking restrictions (Latré et al., 2016) while leaving other city challenges behind.

Solid waste management is one of these challenges, which has been identified as important for integrating sensors towards a sustainable city with a significant impact on quality of life (Ismagilova et al., 2019). According to the World Bank, around 2.24 billion metric tons of municipal solid waste were generated in 2020 worldwide (Kaza et al., 2021). A number that has been increased by medical waste during the COVID-19 pandemic in values between 62% and 350%, according to Yousefi et al. (2021), or between 18% and 425%, according to Liang et al. (2021). Of the overall waste generation, around 33% of them are not being environmentally safely managed every year (Kaza et al., 2018). This issue has the potential to generate several impacts on health: such as infections, body injuries, poisoning, and chronic disease (Ziraba et al., 2016); on sewage systems due to illegal dumping wash-off and drainage blockade (Pervin et al., 2020); on soil quality, when waste leachate percolate the strata and aquifers (Sharma et al., 2018); and can be drivers for potential disease vectors as insects, birds, rodents and other mammals (USAID, 2007).

The United Nations did not include Solid waste management as a primary Sustainable Development Goal – SDG, potentially reducing its visibility in the political agenda (Rodić & Wilson, 2017). However, it has become a significant challenge worldwide that tackling the issue is intrinsically related to twelve of the 17 SDGs, principally SDGs 11, 12, and 13 (Wilson et al., 2015); therefore, it is a critical task to address to achieve sustainability in cities.

1.1. Problem statement

The waste management system comprehends six stages in the urban environment: controlled generation, on-site segregation, collection, transport, storage, and final disposal (Arora et al., 2022). Each has its challenges and needs for integration in the layers of a smart city and the Urban Digital Twin solutions. In the conventional procedure for solid waste management, residents perform generation and segregation at the point of creation. The municipality then handles the collection using a predetermined schedule where trucks gather the solid waste from containers and curbs, whether wholly filled or not (Vishnu et al., 2021), leading to a misuse of resources both in time, fuel, and staff. This stage can represent up to 90% of the municipal solid waste management budget (Hoornweg & Bhada-Tata, 2012). In the transport stage, vehicles move the waste material from collection points to recycling centers or treatment facilities or, more often, to landfills or open disposal sites; finally, elements that are not recovered or recycled are buried, burned, or treated thermally (Kumari et al., 2021).

In South Africa, 30.5 million tons of solid waste were generated in 2017[1], with 34.5% of them being recycled and 11% not having adequate final disposal (Department of Environment Forestry and Fisheries, 2020; Department of Environmental Affairs, 2018). With its population of 59.9 million (United Nations Department of Economic and Social Affairs, 2022) – 56.4 million in 2017 – South Africa has an estimated generation of 1.48 kg/capita/day of solid waste. A value which is higher than the sub-Saharan average – 0.46kg/capita/day – and is at similar levels of the upper quartile of Europe and Central Asia countries – 1.53kg/capita/day (Kaza et al., 2018), being the primary challenge in the overall waste management system of the government.

A national waste management strategy has been in place since 2008 to reduce the generation of solid waste and the amount of it that reaches landfills (National Environmental Management: Waste Act 59 of 2008, 2008). Revisions and updates on this policy in 2011 and 2020 have found that one challenge in reducing the waste disposed of in landfills is littering and illegal dumping (Department of Environment Forestry and Fisheries, 2020), a situation that is occurring due to the lack of regular collection service (L. T. Polasi, 2018), and incomplete coverage in the service distribution (T. Polasi et al., 2020). Additionally, historical inequalities have led to reduced collection services in informal areas and peri-urban communities (Department of Environment Forestry and Fisheries, 2020), as well as a lack of education and awareness in some districts of the country amid a lack of prioritization in the municipal budget for waste management (ibidem).

Moving to a local scale of these challenges, in the city of Tshwane, the metropolitan municipality surrounding Pretoria – South Africa's administrative capital – the irregularity of service has led to protests claiming service delivery and consistency in equal levels as of the apartheid white areas of the city (Mokebe, 2018). The city reports that the solid waste that reaches the landfill per capita is around 1.95kg/d (City of Tshwane, 2022a), indicating a more significant waste production than the national average. With over six hundred illegal dumping hotspots detected, the city has identified measures to improve the solid waste management system, including confirming illegal dumping sites, allocating new containers, and applying intense cleanup of the streets (City of Tshwane, 2022b).

Previous studies have suggested that executing the type of measures identified by the city of Tshwane requires moving from a traditional static model to a dynamic one that adapts to changes in waste generation (Anagnostopoulos et al., 2015). The new model must incorporate real-time container monitoring and frequent collection route optimization (Hina et al., 2020; Ramson et al., 2022). Moreover, the model should include active citizen participation supported by government structures for managing solid waste in a new model of waste governance and sustainability (Serge Kubanza & Simatele, 2020).

1.2. Research Gap

Several sensors implementation have been designed for monitoring solid waste containers. Some include the use of ultrasonic sensors on the lid of the containers (Chaudhari & Bhole, 2018; Joshi et al., 2022; Karthik et al., 2021; Mahajan et al., 2017; Ramson & Moni, 2017), weight sensors at the

[1] Production of residential, commercial, and institutional waste. Does not include construction and demolition waste, industrial, electronic, or hazardous materials.

bottom of the container (Rovetta et al., 2009), a mix of both (Ali et al., 2020; Vicentini et al., 2009) or infrared sensors (Singh et al., 2016), to detect the status of the containers in terms of fullness capacity. The ultrasonic sensor designs of these studies were only tested at the prototype level, including some indoor simulations of the solid waste collection, which is later reported to a centralized system but tested in no more than two containers. This type of sensor still needs to be tested in specific outdoor conditions of the city where it should be implemented and on a scale that it can be installed in several containers and send the signals to a centralized system that the municipality or company in charge of the solid waste collection of a city can operate. Nonetheless, Ali et al. (2020) simulations demonstrated the possibility of creating production records and using them to forecast daily generation levels for each container.

While the studies of Rovetta et al. and Vicentini et al. have tested them outdoors, in Shanghai, PR China, with controlled scenarios for residential and commercial usages, the test made by these authors used operators for the containers. It invited citizens to use those particular containers creating a bias in the actual values of on-site generation. These studies already propose including a route optimization for solid waste collection as a future development and use of the designed sensors. In addition, they do not implement them with real-time information.

Route optimization has been studied for several years with different approaches. The first one is algorithm improvement, where a mathematical method is analyzed to get the most efficient collection route (Erdinç et al., 2019; Hannan et al., 2018; Sahib & Hadi, 2021), showing the possibility of reducing cost based only on the length of the road segments, and how efficiency also implies an additional coverage of for collection due to the extended use of vehicle fuel. A second approach is agent-based modeling, which simulates the generation of solid waste and sequential filling of containers collected on the shortest route between filled containers, maximizing profits for the collection scheme (Likotiko et al., 2017). On a third method, GIS analysis using the ArcGIS Network Analysis tool has been implemented considering the length of routes, topography, and time taken for collection (Hemidat et al., 2017; Jovicic et al., 2010; Malakahmad et al., 2014). Finally, an integration of the three methods has been studied, optimizing the route by a mathematical model, including the road network, traffic data, and collection scheme from GIS data, and testing the model in agent-based model simulation (Nguyen-Trong et al., 2017). These optimizations follow the same vehicle routing problem: 1) where the route should start and end at the depot or landfill, 2) each container is served by only one route, 3) the vehicle capacity limits the collection, and 4) the route must comply with the traffic regulations of each country.

The approaches used for vehicle route optimization have shown reduced operation time and saving in fuel and man resources. Only the study performed by Likotiko et al. (2017) considers consecutive optimizations based on the volume of the container and the constant changes in the generation of solid waste that would require re-optimizing the route when including real-time data. These optimizations aim to deliver a one-fit-for-all solution rather than adapting to the requirements of each area and the dynamic generation of solid waste.

The city of Utrecht, Netherlands, has already incorporated ultrasound sensors and daily rerouting based on the level of fullness containers have, reducing the number of vehicles and preventing overflow of the containers (Gemeente Utrecht, 2021), showing the capabilities that this type of integration have on the minority world. Theoretical approaches for the integration of solid waste sensing and vehicle routing have been discussed by scholars (Ali et al., 2020; Likotiko et al., 2017; Rovetta et al., 2009; Roy et al., 2021) with test scenarios in India, China, and Saudi Arabia. They have included random generation values for solid waste production and using Google Maps API and GIS solutions for routing optimization. However, these approaches do not extend to the scale of neighborhood or city and have not been tested with actual data generation and collection of containers. Therefore, scalable, and transferable methods have been discussed as of high need.

Finally, the Solid Waste management system in Sub-Saharan Africa has not been researched with the Urban Digital Twin approach. Studies in South Africa have focused on a mathematical approach to finding the shortest distance between containers without considering road network restrictions, vehicle capacity, or solid waste production (Mpeta et al., 2020).

As explained above, South Africa's challenges in solid waste management include large generation, collection intermittence, and illegal dumping. These elements can be integrated into an Urban Digital Twin to solve the solid waste management challenges. Thus, this research will focus on the collection stage of the process aiming to create a prototype that incorporates waste generation simulations towards containers and vehicle routing optimization based on the generation and prediction of future volumes. The research is performed in the City of Tshwane, focusing on the Hatfield and Hillcrest neighborhoods as a case study. The research aims to create the first South African digital twin model for solid waste management and propose a prototype that might be replicated in other cities.

1.3. Summary

This research explores integrating urban digital twin technology with solid waste management systems to address the challenges of waste collection, intermittence, and illegal dumping in urban environments. Urban digital twins, dynamic digital replicas of physical urban assets, offer a comprehensive approach to co-create and test scenarios for urban development and sustainability. These digital twins enable simulations, analysis, and informed decision-making by incorporating real-time data. In the context of waste management, sensors for container fullness monitoring and route optimization are gaining traction. However, existing studies often lack scalability, integration with dynamic waste generation patterns, and thorough testing in real-world urban environments.

This research focuses on the City of Tshwane in South Africa, specifically the Hatfield and Hillcrest neighborhoods, as a case study to develop and test a prototype digital twin model for solid waste management. By simulating waste generation patterns, predicting future volumes, and optimizing waste collection routes, this study aims to address the challenges of irregular collection services and inefficient resource utilization. The proposed prototype could be a transferable solution for other cities facing similar solid waste management issues in Sub-Saharan Africa.

By integrating urban digital twin technology, dynamic waste generation modeling and route optimization, this research aims to advance sustainable waste management practices, improve urban cleanliness, reduce environmental impacts, and enhance the overall quality of life in rapidly growing urban areas. This study sets the stage for a novel approach to urban waste management that leverages digital technology and real-time data analytics by bridging the gap between theoretical approaches and practical implementation.

2. Conceptual framework

The concepts and their relationships used in this research are summarized in **Figure 1**. As mentioned above, challenges in the solid waste management collection stage can be improved by including sensing and detecting the generated solid waste. An urban digital twin tool can be implemented as a decision support system to visualize the current state of container capacity, improve the collection routing, predict future generation, and make decisions to improve the overall design. This requires comprehending how stakeholders participate in the decision-making process and the existing methods for route optimization, which are described in the following subsection.

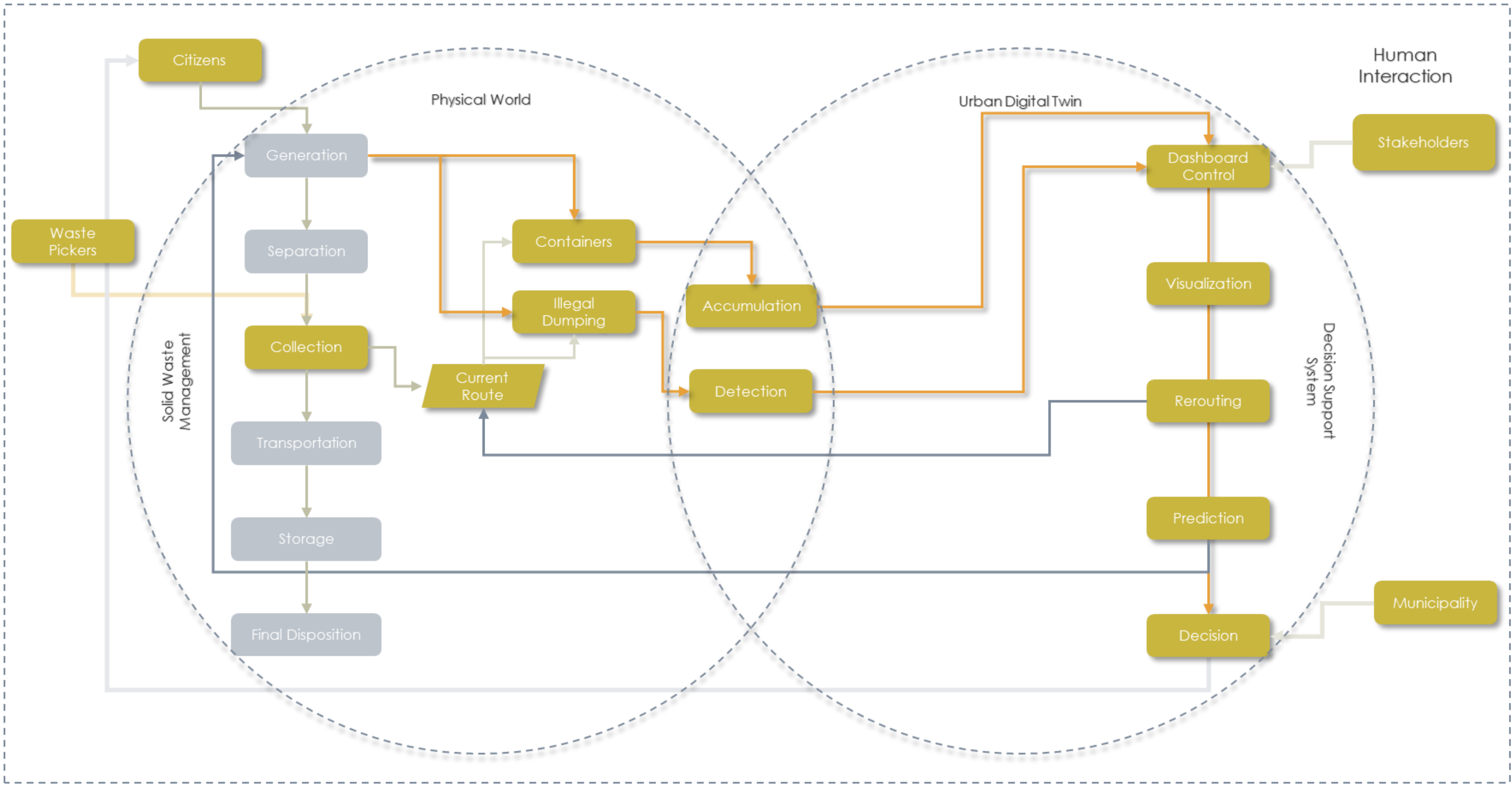

***Figure 1**. Conceptual Framework. The elements in green are included in the research.*

2.1.1. Stakeholders Identification and Classification

As waste management systems include technological, political, environmental, and socio-economic aspects that are interrelated and dynamic, they have many stakeholders (Zaman & Lehmann, 2011). Understanding the stakeholders' characteristics, local conditions, and constraints helps increase participation and improve the effectiveness and willingness to find appropriate solutions.(Lishan et al., 2021; Palacios-Agundez et al., 2014). Therefore, it is necessary to understand who a stakeholder is, their relations among stakeholders in the specific context of a study area, and the particularities of what is at stake (Freeman, 2010).

One of the methods for stakeholder identification was developed by Mitchell et al. (1997), where they proposed a classification system so no potential or actual stakeholder is excluded a priori within the management of an organization. The system includes categorization according to three attributes a stakeholder can possess: **Power**, whether coercive, utilitarian financial, or normative; **Urgency**, referring to the extent to which stakeholder demands require immediate attention. It can be either in time or subjective importance; and **Legitimacy** relates to the social perception that stakeholders' actions and intentions are desired and appropriate within the culture and the *social good*.

Depending on the combination of such attributes, Mitchell et al. define seven typologies of stakeholders based on whether they possess one, two, or three attributes (see **Figure 2**). In this classification, **Dormant** stakeholders possess power but cannot use it as they are not recognized as legitimate and have no urgency in their demands. **Discretionary** ones have social legitimacy without power or urgent claims; in this situation, other stakeholders might not see the need to engage with discretionary stakeholders but can choose to do it. **Demanding** stakeholders only have urgency as their attribute; therefore, they cannot move their claims forward without acquiring other attributes. These three types of stakeholders are recognized as **latent**.

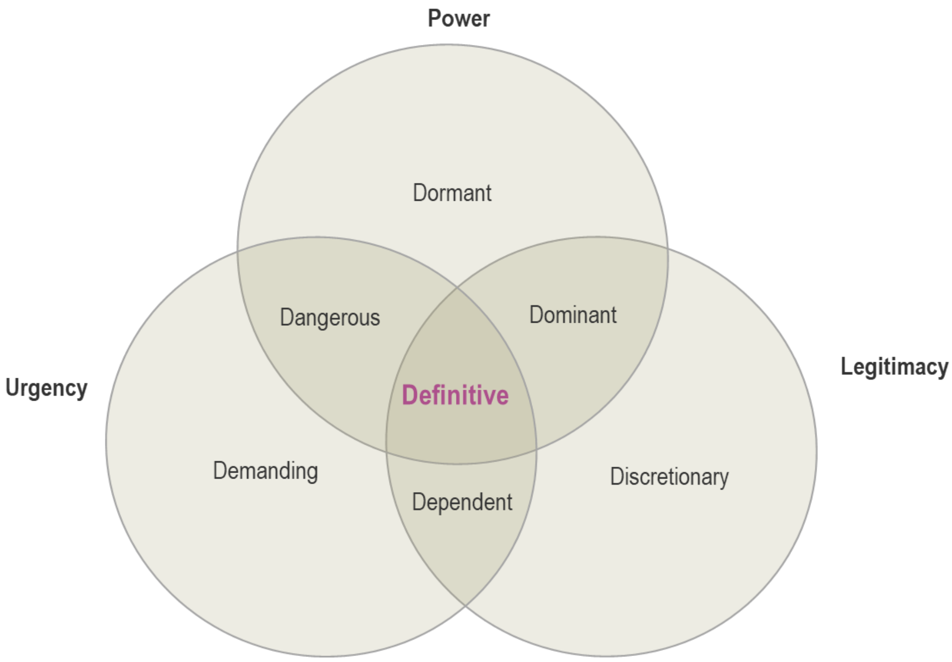

Figure 2. *Stakeholders Typology. One, two or three Attributes Present. Source: Mitchel et al. (1997)*

When stakeholders possess two attributes, they are recognized as **expectant** stakeholders. In this sense, **Dominant** stakeholders possess both power and legitimacy, being able to act on their claims and wishes, but as there is no urgency, they might choose never to act on it. **Dependent** Stakeholders do not possess power; therefore, they need to advocate for a powerful stakeholder to make their claims heard or executed. **Dangerous** stakeholders lack legitimacy, which could translate into coercion and violence to make their claims heard. Finally, when all three attributes are present, definitive stakeholders emerge, and they can start moving their demands and decisions to achieve a selected goal, they are the implementers of change. The dynamics and interactions of stakeholders can move any expectant stakeholder into a salience one either by negotiating or partnering with other stakeholders.

Although this model considers three main attributes, it has been argued that it does not consider vulnerable stakeholders who might not possess any of them (Shafique & Gabriel, 2022), and those models must be "more spatially and temporally inclusive" (Gladwin et al., 1995). As spatial vicinity can contribute to building stakeholder relationships, Driscoll & Starik (2004) suggests physical and social **proximity** as an attribute extending Mitchel et al.'s salience model.

Shafique & Gabriel (2022) have researched this attribute identifying that it is independent of power, urgency, and legitimacy; it co-exists with those attributes and creates additional relationships and typologies (**Figure** 3) for stakeholders' classification. In their findings, they propose and describe eight new typologies (**Table** 1), extending the model and allowing vulnerable stakeholders to be identified and categorized, focusing on project operations rather than just organization management.

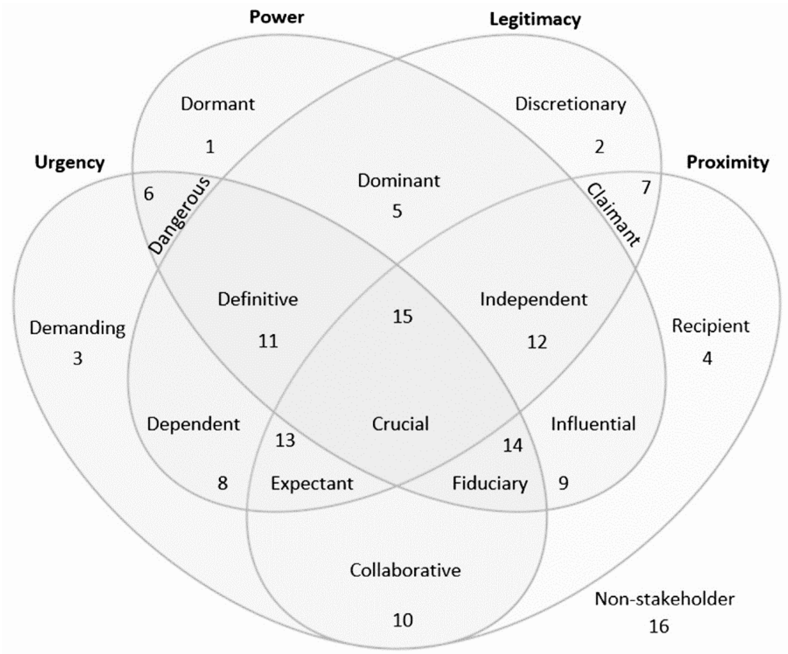

***Figure** 3. Stakeholders' typology with four attributes and their relationships. Source: (Shafique & Gabriel, 2022)*

***Table** 1. Stakeholders' Typology, attributes, and description. Source:Shafique & Gabriel (2022)*

#	NEW TYPOLOGY (ATTRIBUTES)	DESCRIPTION
4	**Recipient (Proximity)**	Recipient stakeholders receive some benefit from the project because they reside in or close to the project implementation area. Although not the project's target beneficiaries, they benefit indirectly from the project because of their physical closeness to its beneficial outcomes.
7	**Claimant (Legitimacy & Proximity)**	Claimant stakeholders have a perceived legitimate role and claim to the project and reside in or close to the project area. They receive a direct benefit from the project outcomes.

#	NEW TYPOLOGY (ATTRIBUTES)	DESCRIPTION
9	**Influential (Power & Proximity)**	Influential stakeholders are powerful and either reside in or have some form of control over the project implementation area.
10	**Collaborative (Urgency & Proximity)**	Collaborative stakeholders do not possess power and legitimacy. However, because they were affected by the disaster due to their closeness to affected areas, they have a high interest in the urgent completion of the reconstruction project. Their collaboration contributes to the success of the project.
12	**Independent (Power, Legitimacy & Proximity)**	Independent stakeholders can implement the project without the help of other stakeholders because of their ability to influence others and the official recognition of their role in implementation. These are usually local stakeholders with a physical presence in the project area.
13	**Expectant (Legitimacy, Urgency & Proximity)**	Expectant stakeholders are not considered powerful but expect to benefit directly from the project because they possess urgency, proximity, and legitimacy attributes. Other stakeholders (though not necessarily project implementers) recognize them as stakeholders, legitimizing their role.
14	**Fiduciary (Power, Urgency & Proximity)**	If collaborative stakeholders acquire power over the project implementation area, they become fiduciary stakeholders. Project managers recognize their responsibility to report directly to these stakeholders on project outcomes. Vulnerable-affected communities might aspire to this role by demanding community-driven approaches to project implementation.
15	**Crucial (Power, Legitimacy, Urgency & Proximity)**	Crucial stakeholders are the decision-makers, implementers, and beneficiaries of the project. Possession of proximity attributes helps them to gain direct benefit from the project. For vulnerable affected communities, the role of a crucial stakeholder is even better than that of a fiduciary stakeholder.

Although the model provides a comprehensive identification and classification system, just as Mitchell et al., the newly suggested model does not consider a method for identifying the possession of each attribute and the relationships between one and another stakeholder. Therefore, the classification tends to be subjective to the researcher's interpretation creating a significant bias on the typology allocation.

2.1.2. Routing Optimization problems

Solid waste collection can be seen as an inversed good distribution problem, where items must be gathered instead of delivered. It is necessary to optimize the waste collection route to make an efficient collection. Therefore, solid waste collection is an optimization problem that depends on the number of collection points, the waiting time for load and unloading, and the accumulated distance from the landfill to collection points and between collection points (Sarmah et al., 2019).

To solve this problem, is it possible to consider it as a Traveling Salesman Problem (TSP), which considers a single vehicle visiting multiple customer locations (nodes) before returning to the depot, where the goal is to minimize the added arc weights (the connection between locations), either if it is travel time or traveled distance between nodes (Herdianti et al., 2021).

The solution of the TSP has been discussed as early as 1956 (Flood, 1956), describing that the goal is to find the minimum permutation from 1 through *n* as described in **(1)**, where $a_{\alpha\beta}$ are a set of real numbers indicating the time or distance between places α and β to visit.

$$a_{1i_2} + a_{i_2 i_3} + a_{i_3 i_4} + \cdots + a_{i_n 1} \tag{1}$$

In its most straightforward formulation, TSP does not have other restrictions, and the problem only depends on the number of locations and the factor that is being measured. When conditions are added to the problem, such as return to the depot after *m* nodes have been visited, where *m* $|(n-1)$; or including several deliverables at every node, the variations are known as TSP generalizations (Dantzig & Ramser, 1959).

In the solid waste collection scenario, it is necessary to include both the conditions mentioned above, as each node has some goods to collect, and the collection vehicle can only visit a limited set of locations before returning to a landfill. Therefore, the TSP transforms into a generalization known as a Vehicle Routing Problem (VRP) that differs from TSP as there is not only one route but multiple possible routes that require visiting all nodes (Herdianti et al., 2021).

As collection vehicles have a limited capacity for carrying goods (waste), their capacity is not uniform, and all node demands are known but variate from node to node; the problem transforms into a combination of Bin Packaging Problem (BPP) and VRP known as Capacitated Vehicle Routing Problem (CVRP) (Herdianti et al., 2021; Ralphs et al., 2003).

Assuming that a vehicle moves at the maximum allowed speed (v) for each segment of edges ij of a length *l*. The objective of a CVRP for optimizing the time of service in the collection of waste will follow the objective of **(2)** with the boundary functions from **(3)** to **(6)**, as similarly explained by Herdianti et al. (2021):

$$Z\,[T] = \min\left(\sum_{k=1}^{r}\sum_{i=0}^{n}\sum_{j=0}^{n}\frac{l_{ij}}{v_{ij}}x_{ijk}\right) \tag{2}$$

$$x_{ijk=}\begin{cases}1, & if\ vehicle\ k\ passes\ the\ route\ from\ i\ to\ j\\ 0, & elsewhere\end{cases}$$

Where i and j are the indexes of nodes $1 \dots n$, and 0 is the landfill. On each node, a quantity d is required to be collected; k is the index of vehicles $1 \dots k$ with capacity Q. The boundary functions are:

- Each node is visited only once by a vehicle.

$$\sum_{i=0}^{n}\sum_{k=1}^{r}x_{ijk} = 1\,, \qquad \forall j = 1,2,\dots,n$$
$$\sum_{j=0}^{n}\sum_{k=1}^{r}x_{ijk} = 1\,, \qquad \forall i = 1,2,\dots,n \tag{3}$$

- The number of vehicles exiting and entering the landfill is the same.

$$\sum_{i=0}^{n}x_{0ik} - \sum_{j=0}^{n}x_{j0k} = 0, \qquad \forall k = 1,2,\dots,n \tag{4}$$

- If the vehicle visited the node, it must also leave.

$$\sum_{i=0}^{n} x_{isk} - \sum_{j=0}^{n} x_{sjk} = 0, \qquad \forall s = 1,2, \dots, n; \ \forall k = 1,2, \dots, n \tag{5}$$

- The waste loaded should not exceed the capacity of the vehicle.

$$\sum_{i=1}^{n} d_j x_{i0k} \leq Q_k, \qquad \forall k = 1,2, \dots, n$$
$$\sum_{j=1}^{n} d_j x_{ik} \leq \sum_{k=1}^{r} Q_k, \qquad \forall k = 1,2, \dots, n \tag{6}$$

Several methods have been studied for solving TS and VR, and CVR problems through the years that can be grouped into three types of algorithms as described by (Avdoshin & Beresneva, 2019):

- **Exact Algorithms** find the optimal solution for the problem but take a long time to solve large problems. Solutions for up to one hundred nodes can take 30 – 40 minutes on average (Braekers et al., 2016)
- **Classic heuristic algorithms** provide an approximate solution to a problem-dependant technique by performing inter-route moves. Once a solution is found, the solution stops and is never improved. The process is done with moves such as removing consecutive nodes from a route and re-inserting them somewhere, swapping consecutive nodes between routes, or removing edges to reconnect nodes in a different way (Braekers et al., 2016; Laporte et al., 2014). Several methods can be applied among these solutions, such as Nearest Neighbor, Greedy, Insertion, and Christofides heuristics (Laporte et al., 2014).
- **Metaheuristics algorithms** are problem-independent techniques being foundations for building heuristics. This type of algorithm explores solutions by moving from a solution to a neighbor solution, even accepting a temporal detriment on the current iteration, to find a better global result (Local Search) (Avdoshin & Beresneva, 2019; Laporte et al., 2014). Among these solutions exists Simulated Annealing, Deterministic Annealing, Tabú Search, Iterated Local Search, and Variable Neighborhood Search algorithms (Laporte et al., 2014; Nilsson, 2003).
  The metaheuristics can also *evolve* a group of solutions to generate a better one once the solutions are combined, called population-based or evolutionary algorithms. These algorithms combine guidance methods, such as neural networks, pools of solutions, or pheromone matrices, with the local search algorithms to find a solution (Avdoshin & Beresneva, 2019; Laporte et al., 2014). Ant Colony Optimization, Genetic Algorithms, Scatter Search and Path Relinking, and Learning Mechanisms are among these algorithms. (Laporte et al., 2014)

This research will use the nearest insertion heuristics combined with the Tabú search metaheuristic method from ESRI for solving the CVRP (ESRI, 2023b). In the nearest insertion, the problem solution selects the shortest edge and performs a sub-solution of it, then selects a node not in the solution with the shortest edge to create consecutive nodes; it follows by finding an edge where the insertion of the consecutive nodes will be the minimal accumulation between previously solved nodes (Nilsson, 2003). The Tabú search method allows moves with a negative gain if a positive has not been found. The algorithm creates a list of illegal moves to avoid infinite circular loops. Once a neighboring solution is chosen, it will be added to the tabu list, ensuring that it is not revisited unless it leads to an improved tour or is removed from the list (Nilsson, 2003).

2.2. OBJECTIVES

To develop an Urban Digital Twin prototype for improved solid waste management involving citizen science in South Africa.

2.2.1. SO1: To explore the current methods for operational planning of solid waste collection.

a. What geospatial or remote sensing data types are used for the solid waste collection scheme?
b. What is the current planning scheme for solid waste collection in the City of Tshwane?
c. Which stakeholders and relationships are involved in solid waste management in the City of Tshwane?

2.2.2. SO2: To design an Urban Digital Twin prototype for Solid Waste Management

a. Which parameters should be considered for developing the Urban Digital Twin prototype?
b. What are the spatial distribution and characteristics of collection points and illegal dumping sites?
c. How to integrate different data sources in near-real time?
d. How to apply the selected methods for urban digital twins' prototype development?

2.2.3. SO3: To evaluate the Urban Digital Twin prototype performance.

a. How is the performance of the Urban Digital Twin prototype as seen by stakeholders?
b. What is the added value of the developed prototype compared to traditional collection methods?
c. Which characteristics of the prototype could be improved for further research and implementation?

3. STUDY AREA AND DATASETS

The study focused on the Hatfield and Hillcrest neighborhoods of the capital city of South Africa, Pretoria. The area comprises 9.45 km² surrounding the University of Pretoria main campus (See **Figure** 4) with different land uses such as residential, institutional (embassies), commercial, agricultural, and educational. This area is part of the ongoing project of African Future Cities from the Department of Architecture in the Faculty of Engineering, Built Environment, and Information Technology of the University of Pretoria.

***Figure** 4. Hatfield Digital Twin City Study Area.*

3.1.1. Hatfield City Improvement District

The area also includes the Hatfield City Improvement District (CID) (see **Figure** 5). This non-profit and private organization performs corporate governance of the area. It is funded by a taxpayer's property levy collected by the municipality and transferred to the Hatfield CID for operation, providing additional services such as cleaning and maintaining public spaces, private security, and urban embellishment (Hatfield CID, 2021).

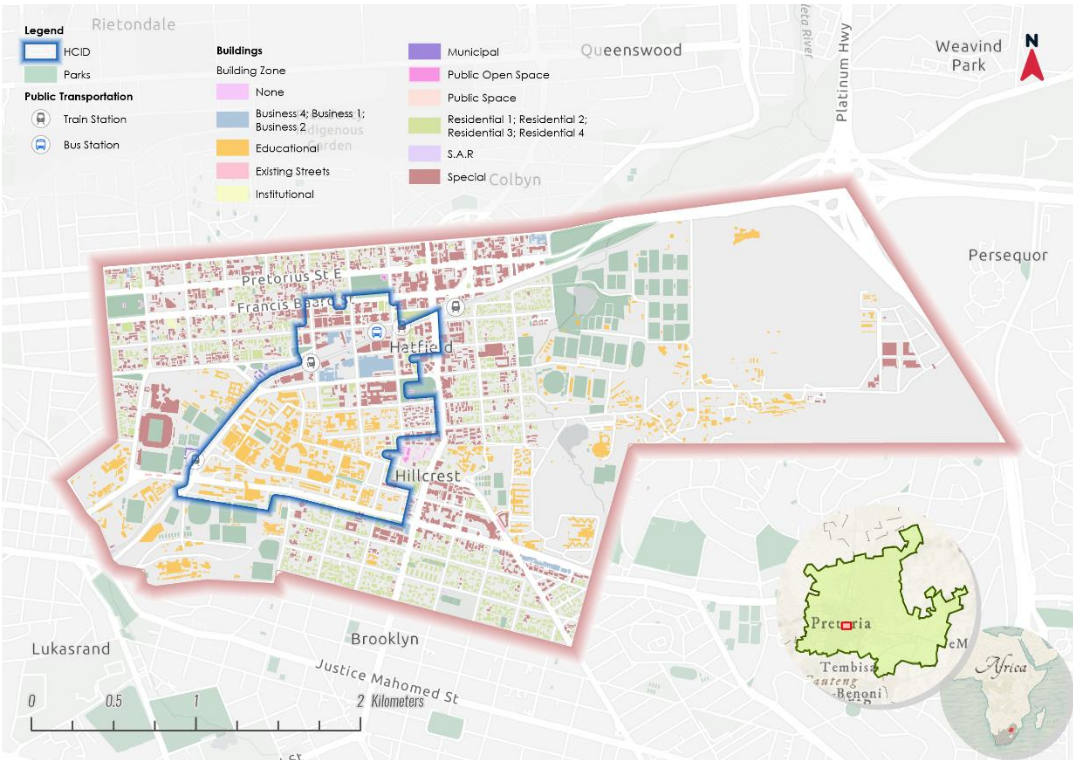

***Figure** 5. Hatfield City Improvement District limits*

3.1.2. Geospatial Datasets

The research was supported with geospatial data from the City of Tshwane, the National Geo-Spatial Information Centre of South Africa, and data collected by the Faculty of Engineering, Built Environment, and Information Technology of the University of Pretoria. The initial data required for the research are summarized in **Table** 4, including data type and sources of information. To use in a web environment, all data was reprojected to WGS 1984 (ESPG: 4326). Nonetheless, length and area attributes were calculated in Hartebeesthoek94 / Lo29 (ESPG: 2053).

***Table** 2. Initial used Dataset description*

Geospatial dataset	Specifications	Data type	Date	Coordinate system	Source
LIDAR Scanning	Aerial Laser Scanning with 0.6m of separation.	LAS	June, 2019	EPSG: 4148	University of Pretoria, ESRI
Buildings	Building footprints with attributes Name, type of building	Vector Polygons	March, 2023	EPSG: 4326	OpenStreetMap Contributors
Road Network	Polyline of the Vehicle roads, including total length, road direction, road type	Vector Lines	March, 2023	EPSG: 2053	City of Tshwane GIS Portal
Aerial Imagery	Very High-Resolution Imagery from Unmanned aerial vehicles - UAV from the study area. RGB bands. 0.1m spatial resolution.	Raster	June, 2018	EPSG: 2053	City of Tshwane GIS Portal (2018) – Aerial imagery 1cm spatial resolution: 10cm
Zoning	Polygons defining regulations for land use.	Vector Polygons	March, 2023	EPSG:2053	City of Twhswane GIS Portal
Global Settlement Population	Estimated Residential population per 100x100m cell. Epoch 2020.	Raster	June, 2022	EPSG:54009	GHS population grid multitemporal (1975-2030). European Commission, Joint Research Centre (JRC)

4. METHODOLOGY

To answer the research questions, this research consisted of five phases where both quantitative and qualitative methods were used to achieve the sub-objectives and respond to the research questions raised. **Figure** 6 summarizes the methodology workflow of the research, which is detailed in the following subsections.

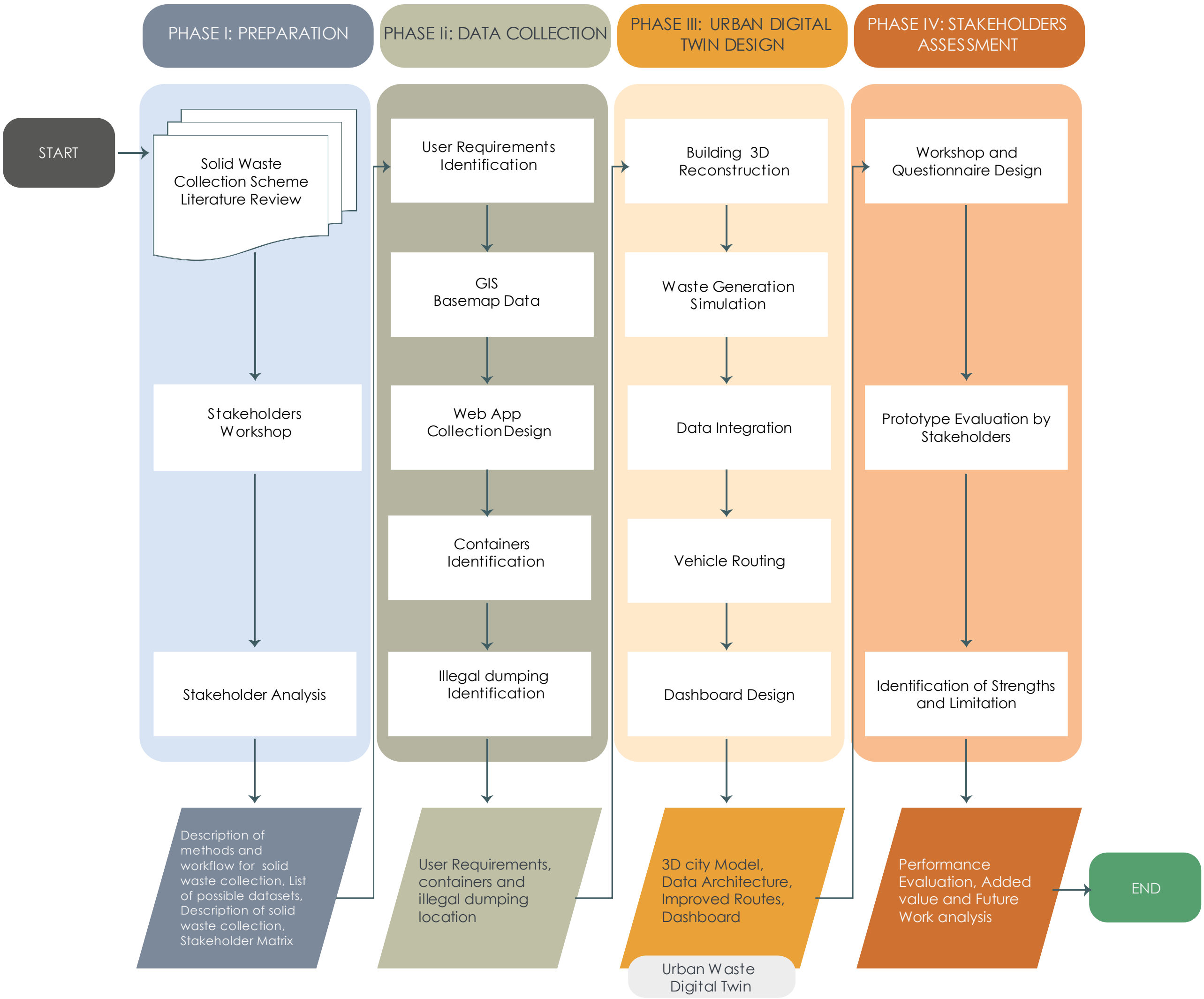

***Figure** 6. Methodological Flowchart of the research process*

4.1. Phase I: Preparation

4.1.1. Stakeholders' Identification and Expectations

Based on an unstructured interview with a key informant, a stakeholders' workshop took place on the 31st of January 2023. The activity focused on understanding the dynamics and relationships of the stakeholders and their expectations and requirements to improve solid waste collection management. Such requirements were asked to the stakeholders, separating them into three categories: Strategic, Operational, and Performance.

The workshop was video recorded. Authorization of the participants, and a transcript was generated using the method developed by Radford et al. (2022). The text was analyzed by identifying additional stakeholders and the relationships of Power, Urgency, Legitimacy, and Proximity that exist between all of them and classified them on the typologies of the Salient Model (Mitchell et al., 1997; Shafique & Gabriel, 2022).

To perform such classification and reduce the subjectivity, a pairwise comparison was made using the Analytical Hierarchical Process described by Saaty and Saaty (R. W. Saaty, 1987; T. L. Saaty, 1990). Each attribute was compared on a nine-point scale of their attribute level when stakeholder *i* is compared with stakeholder *j,* as explained in **Table 3**.

Table 3. *Analythical Heirachical Process pair-wise comparisson. Source:* (T. L. Saaty, 1990)

Relative Importance	Definition – X: power, urgency, legitimacy, proximity
1	*i* and *j* have equal X
3	*i* have moderate X over *j*
5	*i* have strong X over *j*
7	*i* have very strong X over *j*
9	*i* have extreme X over *j*
2, 4, 6, 8	Intermediate values between two adjacent judgments
Reciprocal	When the relation is inverse – (eg. *j* has strong X over *i:* 1/5)

Values are then normalized, and based on the resultant eigenvector of each attribute, the different stakeholders were classified on the typologies of the Salience model. On this classification, stakeholders classified as **Definitive and Crucial** were considered the primary end users of the Digital Twin.

4.2. Phase II: Data Collection

4.2.1. Solid Waste Containers and Littering identification

A survey was created using the Epcicollect5 tool developed by Aanensen et al. (2014), including the questions in **Table 4**. The data was collected by, in three days, between 28 February and 02 March, fifteen bachelor's students in their final year of the Architecture program at the University of Pretoria.

The survey was sent to the students with a detailed guide on downloading and using Epicollect5 [2]on a mobile phone (see Annex 11.1). Likewise, an introductory session explaining the tool's usage was delivered to students, and they were asked to keep an accuracy of more than five meters at the moment of collection. The records with an accuracy of less than 20 meters were excluded from the final dataset.

Table 4. *Survey design for Solid waste Containers and Littering identification.*

CATEGORY	QUESTION	DATA TYPE	DOMAINS	REQUIRED	OPTIONAL
Basic Information	Report Date Report Time Where is the report located?	Date Date Geopoint		X X X	
Report Type	What kind of report do you want to make?	String	Litter Report Register a Trash Bin Other Report	X	

[2] https://five.epicollect.net/

CATEGORY	QUESTION	DATA TYPE	DOMAINS	REQUIRED	OPTIONAL
Trash Bin Information	What is the Status of the container	Boolean	Broken Non-Broken	X	
	Is the bin movable?	Boolean	Movable Fixed (static)	X	
	Height (in m)	Double			X
	Radius in m (if circle)	Double			X
	Length in m (if rectangular)	Double			X
	Width in m (if rectangular)	Double			X
	Can you estimate the capacity (in Cubic meters)	Double			X
	Please include a photograph of the container	Photo			X
	Comments	String			X
Litter Report	Severity (How much tras is there)	Integer	Minimal (1) Moderate (3) Severe (5)	X	
	Please include a photograph of the container	Photo			X
	Comments	String			X

The obtained data was extracted using Epicollect5 API through the PyEpiCollect library developed by Principe & Masera (2020), transformed using Geopandas, and stored as a GeoJSON file and ESRI's Shapefile. To simplify and reduce the time of calculations for next steps, containers that are located in a radius of 25m (half of the maximum walking distance recommended by Viktorin et al. (2023)) were aggregated into a single point in the centroid of them, total volume capacity was summed for each point as well as the total number of containers. The aggregation process followed the workflow shown in **Figure** 7 with the Aggregate points tool from ESRI (2023a).

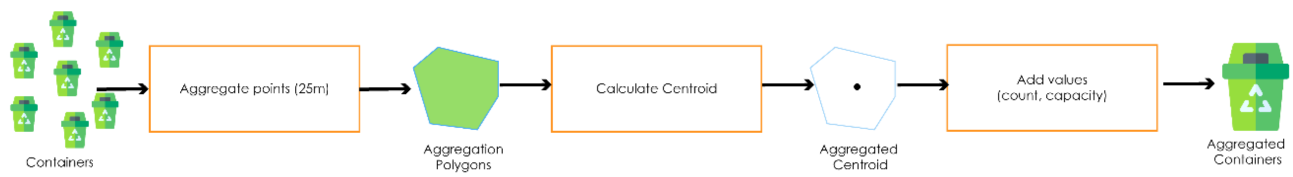

***Figure** 7. Container Aggregation Workflow.*

4.3. Phase III: Urban Waste Management Digital Twin Design

Phase III comprehends a series of steps for the design of the Urban Digital Twin tool. It comprehends city reconstruction, waste calculation, route optimization, and system integration. In **Figure** 8, there is a detailed flowchart that summarizes the process.

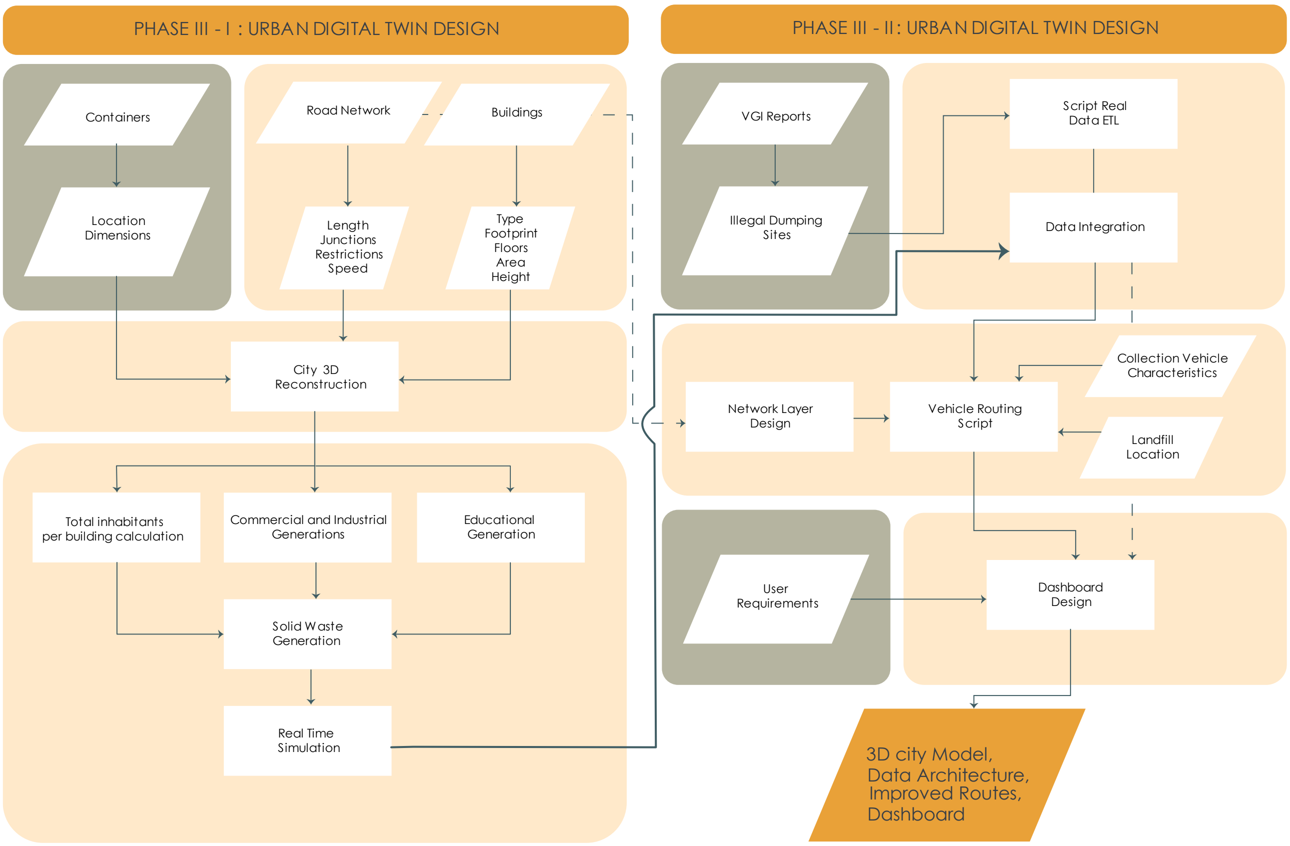

***Figure** 8. Phase III: Urban Digital Twin Design Flowchart. Elements in light green come from phase II.*

4.3.1. System Architecture and Data Integration

Integrating the elements in one Digital Twin tool followed the architecture proposed in **Figure 9**. To create an online, easily accessible control tool, a Dashboard was developed, including the stakeholders' user requirements identified in Phase I (See 4.1).

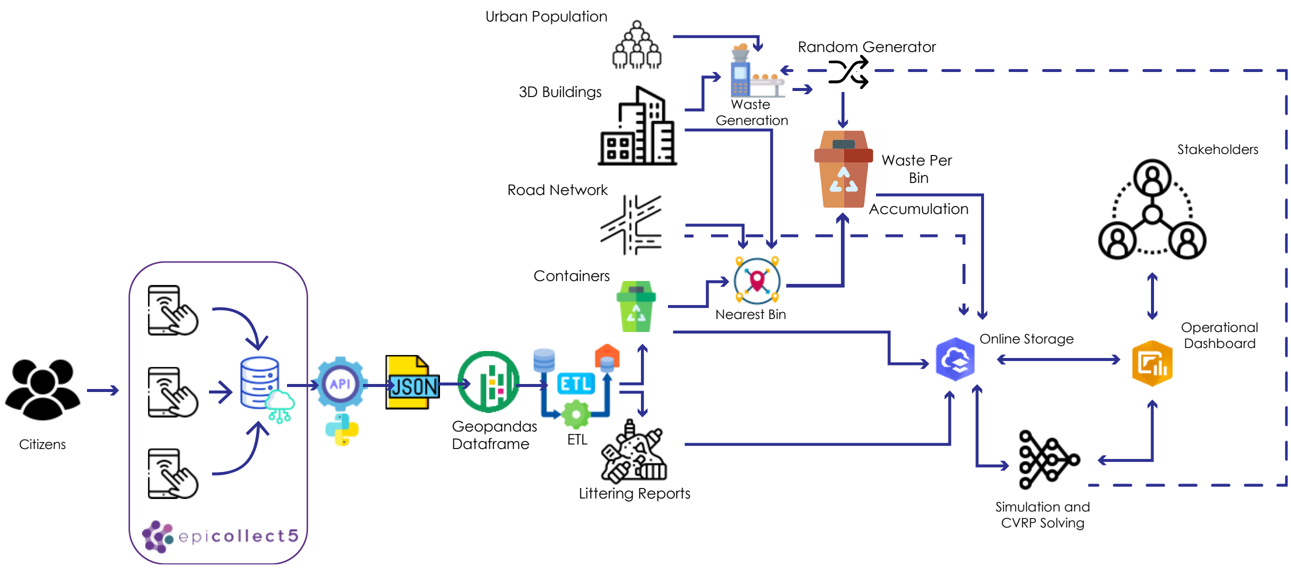

***Figure 9**. Waste Digital Twin Architecture*

The process includes retrieving citizens' collected data through Epicollect5 API that is exported to a JSON file, filtered, and transformed into a CSV point file that can be converted to a point layer to display the containers. Then, the container allocation for buildings is assigned using the near function described in section 4.3.3. The optimal route calculation from section 4.3.4 is calculated, and the resulting route and pick-up sequence is displayed in an operational Dashboard where layers on the dashboard are updated every 6 seconds. The dashboard contains descriptive statistics and the key elements identified by stakeholders from section 4.1.1.

4.3.2. City Buildings reconstruction

An areial LIDAR scanning from Jun-2019, with a spatial accuracy of 60cm, was classified into five categories: ground, noise, low vegetation, high vegetation, and building points. OpenStreetMaps – OSM – building footprints (OpenStreetMap contributors, 2023) were used to help the building classification by performing a 2D intersection that differentiated the vegetation from the buildings.

Later, the building points were transformed into a flat raster (no Z values) where void areas were filled in at a distance of 1.2m (double the pixel size). The resulting raster was transformed into polygons on which edges angles were normalized into right angles and diagonals to obtain geometrically valid polygons. The final polygons were, once again, compared with the OSM to extract the footprints that the OSM contributors had not mapped. Both footprints were merged into a single file containing the complete building footprints of the study area. The quality of the result was tested with a confusion matrix analyzing 1,000 random point locations in the study area. To improve quality, identified polygons with areas smaller than 25 m^2 and heights > 3m were inspected visually to detect and eliminate false positive results that generally were related to trees.

With the ground classification of the LIDAR point cloud, a Digital Terrain Model, Digital Surface Model, and Normalized Digital Surface Model were generated. Together with the building footprint, these were used to extract the base elevation of the buildings, average height, and rooftop form by classifying them as Flat, Shed, Gable, Hip, Mansard, Dome, Vault, or Spherical. This classification is used for the 3D representation of the roofs and to apply procedural textures.

The attributes number of stories above ground, class, function, and usage from the CityGML 3.0 model were used to have more extensive information on the building's attributes. The data for each building was obtained by combining OSM information, City of Tshwane zoning (City of Tshwane, 2023), and on-field validation of the attributes. This validation was performed by a group of 76 first-year Architecture students at the University of Pretoria. Additionally, for each building, the total floor area was calculated by dividing the height into 2.4 meters – The minimum required height for rooms in Tshwane (City of Tshwane, 2014) – and multiplying this value for the footprint area to obtain the total floor area. A UAV Image was used to perform quality control in classifying buildings and determine their usage where on-field validation was not possible.

4.3.3. Solid Waste generation calculation

To obtain an estimation of the population residing in each building of the study area, it was employed the Global Human Settlement Population Layer (Schiavina et al., 2022) on a 100m resolution calculating the population density for each pixel based on the total floor area of residential buildings inside each polygon. The population density value mentioned above was used to derive the population count for each residential building. The resulting inhabitants' calculation was then multiplied by the average waste production value, allowing us to estimate the daily waste production per building.

Non-residential buildings were categorized into four classes with production per class as described in **Table** 5. These categories are organized from higher to lower generation rates, and the waste production corresponds to the upper tier of the range indicated for each class by Karadimas & Loumos (2008).

***Table** 5. Building Classes, related commercial activity, and Waste production. Source: Adopted from (Karadimas & Loumos, 2008)*

Category	Typical Commercial Activity	Waste production (kg/m^2-d)
A	Supermarket, bakery, restaurant, grocery store, greengrocery store, fish store, fast food, bar, pub, club, café.	0.419
B	Butcher store, patisserie, hairdresser, wine-vault, floristry, garage, pizzeria.	0.225
C	Theatre, church, school, bookstore, barbershop, traditional café, pharmacy, post office, lingerie.	0.124
D	Embassy, office, Insurance company, chapel, betting shop, tutoring center, shoe store, clothing store, jewelry store, video club.	0.024

For each building, the closest container, on an "as crow flies" method, was assigned to indicate where solid waste might be deposited and collected. A 600kg/m3 waste density was also assigned as the collection company's operational estimation for its current routing scheme. To simulate the waste production at each location, a random number between 0 and $1/24^{th}$ of the total daily production was generated using Script 1, where a maximum excess of the daily production was set to 20%.

Script 1. Random generation of waste. See also [Github code]

Input:	A geospatial vector point layer with the attributes: Waste daily production (in m^3), Current waste generation (of the simulated hour), Accumulated waste (m^3), Container Volume (m^3), Saturation (%)
Output:	Random accumulation of waste in each container location Accumulated waste Saturation of each container
PROCEDURE: LINE	**DESCRIPTION**
1	Define a function called "generate_random_values" with a parameter "in_layer."
4	Convert the input layer to a string and assign it to the variable "path."
8	Iterate over the rows in the layer using a UpdateCursor.
9	Generate a random value between 0 and the first Waste daily Production value divided by 24 and assign it to "n".
11	Update the Current waste with the random value "n."
14	Calculate the accumulated value by taking the minimum of the sum of the accumulated value and "n" and 1.2 times the first field value. Assign it to "accumulated_value."
17	Update the Accumulated Waste field with the accumulated value.
20	Update the "Saturation" attribute by dividing the accumulated value by the Volumen field value, multiplying it by 100, and assigning it to "saturation".
21	If there is an exception during the calculation, pass and continue.
24	Update the row with the modified field values.

4.3.4. Optimal Collection route

A network analysis was performed using a Capacitated Vehicle Routing problem solver (ESRI, 2023c) to calculate the optimal collection route. The model for the route solution included several factors, such as the aggregated containers' location, their current volume to be collected, the saturation, and limitations by vehicle capacity.

First, the road vector layer was classified to identify monodirectional and bi-directional segments. Their category (residential, highway, link) and the speed of vehicles are restricted to transit. The second step includes creating a Network analysis layer and identifying edges and nodes. Here, each edge weight was calculated according to the time needed to travel the road segment using each segment's maximum speed and length (See Script 2).

Script 2. Pseudo code description creating Network Analysis Layer. See also Github code

Input:	1. A geospatial vector line layer with the attributes: Length (m), speed (km/h), One-way (Y/N) **2.** An XML template defines the road network configuration: Travel mode, impedance attribute, and allowed U-turns.
Output:	Network dataset layer for Network Analysis
PROCEDURE:	
LINE	**DESCRIPTION**
1	Define a function called "createNetwork" with parameters "roads" and "template."
4-8	Check if the Network Analyst license is available. If available, check out the license and display a message. If not available, raise an error.
9	Set the "overwriteOutput" environment setting to True.
10	Set the "workspace" variable to the scratch geodatabase.
11	Set the "folder" variable to the scratch folder path.
12	Get the spatial reference of the "roads" dataset and assign it to the "spatial_ref" variable.
13	Create a new spatial reference object with the WKID 3857 and assign it to the "sr" variable.
14	Display a message indicating the spatial reference.
15	Create a " Network " feature dataset in the workspace using the "sr" spatial reference.
17	Copy the "roads" dataset to the "Network" feature dataset in the workspace.
18	Pause the execution for 20 seconds.
19	Create a network dataset using the provided template in the "Network" feature dataset in the workspace.
20	Build the network dataset.
21	Set the "network" variable to the path of the built network dataset.
22	Display a message indicating that the network was created.
24	Return the network dataset path.

The third step corresponds to selecting such containers where saturation is higher than 75% (this is an arbitrary value that was selected as ¾ of the capacity of the container) and loading them in the network as collection orders. Following this, the conditions of analysis are configured including the starting and ending point at the landfill, the capability of the trucks to dump waste in the landfill, starting time, fuel cost per km, and maximum collection orders.

Once the network is configured, waste is accumulated as described in the previous section, and the problem-solving process occurs every sixth iteration (skipping the 24^{th} one to represent night and non-working collection hours), using a method developed by ESRI. The process starts by creating an OD matrix representing the shortest path between the collection orders and the landfill location. Collection orders are added one at a time to the best route, and the process is enhanced on a tabu search metaheuristic approach to find an optimal solution (ESRI, 2023b)

Once the solution has been found, inserted containers' current waste and saturation are reset to zero, representing a clean-up or collection of the containers. Meanwhile, the non-collected orders keep accumulating until their saturation reaches the threshold. After each clean-up, routes, and orders are deleted to make space for the new route and avoid memory overload. The overall process can be seen in Script 3.

Script 3. Pseudocode description of Vehicle Routing Problem Solver. See also Github code

Input:

1. Network Analysis layer – from the previous step
2. Orders: A geospatial vector point layer with the attributes: A geospatial vector point layer with the attributes: Waste daily production (in m^3), Current waste generation (of the simulated hour), Accumulated waste (m^3), Container Volume (m^3), Saturation (%)
3. Landfill entrance: A geospatial vector point layer with the attributes: Name (String)
4. Truck Route: A geospatial vector line layer with the attributes: Name (string), Capacity (m3)
5. Renewal Conditions: A **Table** with the attributes: RouteName (same Name as input 4), DepotName (same Name as input 3)
6. Folder for storage
7. OutRoute: An EMPTY geospatial vector line layer with the attributes: "OrderCount" (Integer), "TotalTime" (Double), "DistanceCost" (double), "TotalDistance"(double), "RenewalCount"(Integer)
8. OutOrders: An EMPTY geospatial vector point layer with the attributes: "Name"(String), "PickupQuantity" (Double), "Sequence" (Integer), "ArriveTime" (DateTime), "DistanceToNetwork" (Double)

Output: Optimized collection route

Procedure:

Line	**Description**
1	Define a function called "VRP" with parameters "network", "in_orders", "in_depots", "in_routes", "in_renewal", "output_dir", "out_route", and "out_orders".
4-8	Check if the Network Analyst license is available. If available, check out the license and display a message. If not available, raise an error.
10	Import the Network Analyst toolbox.
13	Set the workspace to the output geodatabase and enable overwrite output.
16	Set the "input_gdb" variable to the scratch geodatabase.
20	Set the "layer_name" variable to "Truck Routes".
21	Set the travel mode to "Waste Truck".
22	Set the time units to "Minutes".
23	Set the distance units to "Kilometers".
28	Create a Vehicle Routing Problem (VRP) analysis layer using the provided parameters.
32	Get the layer object from the VRP analysis result.
37-44	Get the names of sublayers within the VRP layer and assign them to variables.
48	Select the containers to be collected based on a condition.

Procedure: Line	**Description**
52	Get the candidate fields from the selected containers.
53-55	Map the fields of the containers to the corresponding properties of the orders in the VRP layer.
56	Load the containers as orders into the VRP layer using the field mappings.
61	Map the fields of the depots to the corresponding properties of the depots in the VRP layer.
62-63	Load the depots into the VRP layer using the field mappings.
67-79	Map the fields of the routes to the corresponding properties of the routes in the VRP layer.
80-81	Load the routes into the VRP layer using the field mappings.
85-88	Map the route renewals' fields to the route renewals' corresponding properties in the VRP layer.
89	Load the route renewals into the VRP layer using the field mappings.
92	Solve the VRP layer.
95	Save the solved VRP layer as a layer file.
99	Share the routes from the VRP analysis as route layers.
102-109	Copy the route layer's attributes to the output route feature class.
112-119	Copy the order layer's attributes to the output orders feature class.
123	Selectively clear the selection on the input orders layer.
126-130	Add the result layer to the current map in ArcGIS Pro.
132	Return the result of the VRP analysis.

4.4. Phase IV: Assessment

On the 12th of July 2023, A workshop demonstration of the Urban digital twin was performed with 21 stakeholders showing them the possible interactions and data that can be visualized and operated in the digital twin control dashboard. The overall development process of the digital twin was shown to the attendants along with a Demo video (See Attachment 11.3) of the functionality. They could use the tool freely after the video, and a questionnaire was delivered to the participants to evaluate the prototype.

The questionnaire was designed with questions on a five-point Likert scale aiming to evaluate the user's satisfaction, as shown in **Annex 11.3**. It measures the usability and usefulness following the method proposed by Ballatore et al. (2020) and the added value analysis proposed by Pelzer et al. (2014) at the group and outcome levels (See **Figure** 10). The evaluation of the Digital Twin was analyzed and discussed following the Gemini Principles (Bolton A & Schooling, 2018) in their three classes: purpose, trust, and function (**Figure** 11).

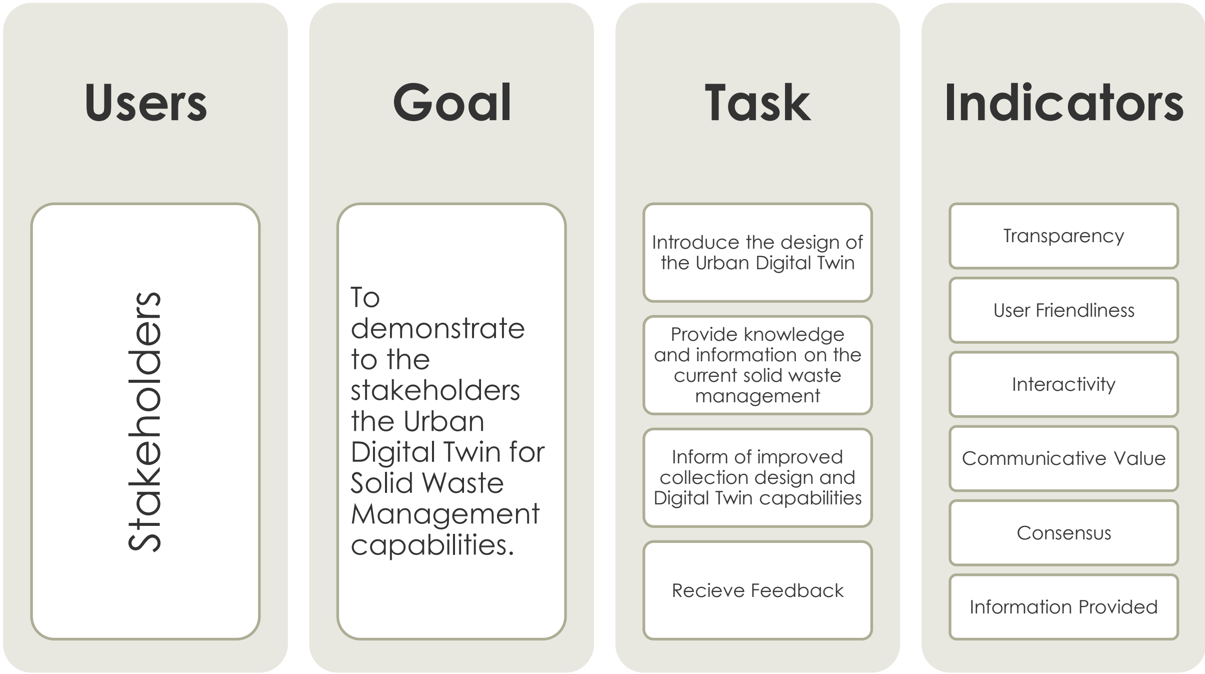

***Figure** 10. Assessment Framework.*
Source : adaptation (Aguilar et al., 2021 ; Ballatore et al., 2020 ; Pelzer et al., 2014)

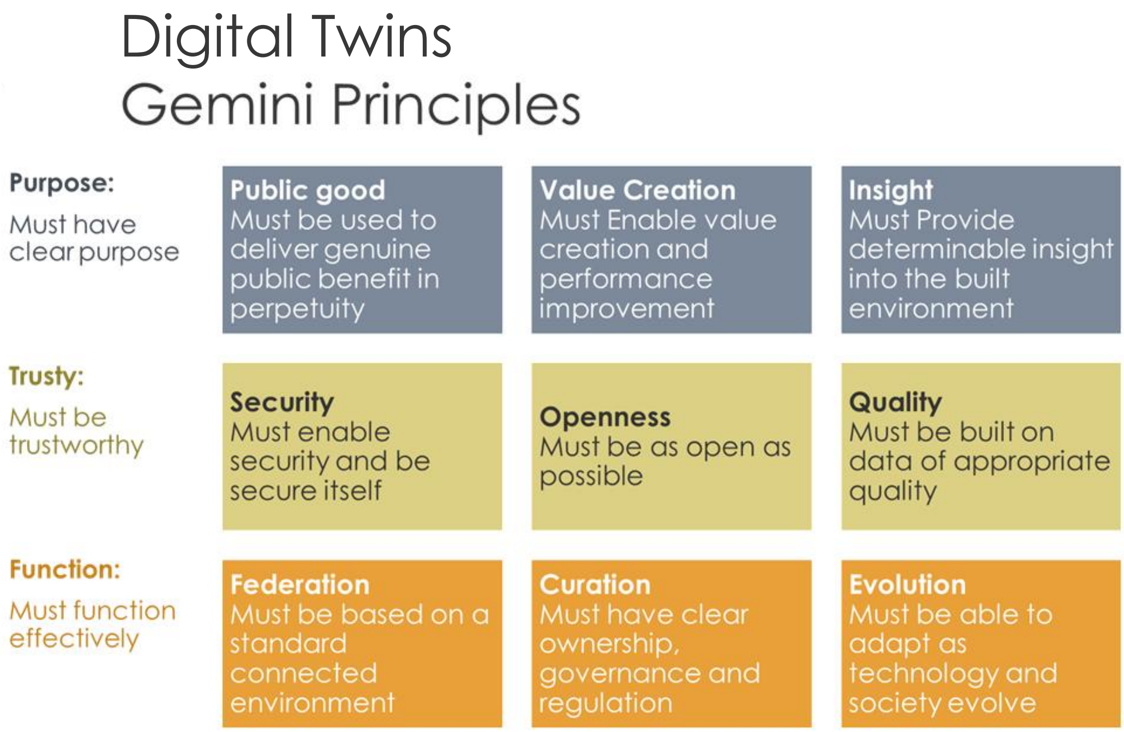

***Figure** 11. Digital Twins Gemini Principles. Source: (Bolton A & Schooling, 2018)*

4.5. Summary

The research unfolds in four phases, employing quantitative and qualitative methodologies to achieve its objectives. In Phase I, stakeholder identification and expectations were elucidated via an unstructured interview and a subsequent workshop, categorizing stakeholder requirements into three distinct domains: Strategic, Operational, and Performance. This classification was conducted using a structured analytical process, incorporating the Analytical Hierarchical Process (AHP) for objective pairwise comparisons and Salience Model Classification.

Phase II involved data collection utilizing a survey tool, EpiCollect5, with final-year Architecture students over three days. This survey captured crucial information on solid waste containers and littering occurrences, subsequently aggregated and processed using Geopandas to create spatial representations of waste-related parameters. Phase III embarked on the design of the Urban Waste Management Digital Twin, encompassing processes of city reconstruction, waste generation estimation, route optimization, and system integration. Utilizing LIDAR scanning and OpenStreetMap data, building footprints and attributes were derived, serving as inputs for waste generation estimations, which were further refined based on population density and building classifications. A vehicle routing problem was then formulated to optimize collection routes, considering container saturation, vehicle capacity, and route renewals. A tabu search metaheuristic was employed to address route optimization.

Phase IV culminated in a workshop demonstration of the Urban Digital Twin, wherein stakeholders were given hands-on experience with the digital twin control dashboard. A Likert-scale questionnaire was administered to evaluate user satisfaction, usability, and usefulness, yielding insights into the tool's efficacy. The study concludes by contextualizing the digital twin's evaluation within the Gemini Principles, emphasizing the aspects of purpose, trust, and function.

5. RESULTS

5.1. Current Practices and Stakeholders

5.1.1. Tshwane current Waste collection scheme

According to the Community survey report of the Province of Gauteng (Statistics South Africa, 2018), the city of Tshwane had 2,921,488 inhabitants in 2011 and 3,275,152 in 2016. This indicates an average annual growth of 2.28%. Calculating the value for 2023, with the same growth rate, the city now has an approximated population of 3,835,010 inhabitants.

As early as 1995, the Gauteng Province records an urbanization level of 94% (Central Statistics Service, 1997). Likewise, the 2011 census shows that the city of Tshwane had an urbanization level of 92.3% (Statistics South Africa, 2012). Assuming there has not been a considerable change on this level, the total population in the urban area of Tshwane is 3,539,714 inhabitants in 2023. At a rate of 1.95 kg/inhabitant-d (City of Tshwane, 2022a), the overall production is 6,902.44 Tons/day of waste for residential, commercial, and industrial waste.

The stakeholder workshop provides information to understand the city's collection scheme process. Generally, the municipality collects the waste of residences and businesses once every week on 18m^3 compacter vehicles that have an efficiency of 4km/L of Diesel. Each suburb has its designated day, and collection companies only control the type of building and number of residential units in each suburb. Due to their high waste production, restaurants get their waste collected daily. Additionally, individual businesses can contract a private waste collection company to provide the service in their required conditions.

> *"[For] business, there [is]an option or a daily collection as well. It's a different kind of bin. But, as far as I know, it's not sorted. It's not recyclable in terms of the sorting. So, it's not differentiated, but it's just a regular collection on a daily basis"* – CID.

The municipality also has a team of foot workers in the public area who deal with pedestrian and vehicle littering. They are provided with bags for picking up the litter, which is then moved to central points were trucks can collect them. Contrary to the truck collection, foot personnel do not work on a scheduled basis. Instead, they do so in an "as the need arises" approach.

The CID provides a littering picking improved service on the streets, sidewalks, and parks of their service area with 16 foot workers and one truck. For the picking, the municipality provides them with garbage bags of around 70,000 to 80,000 bags of waste yearly, registered by each worker and their supervisor in a manual scorecard log.

Within the CID, the working schedule for foot workers follows a standardized time-table. From 7 am to 11 am they perform litter picking in their designated area of around 1 to 1.5 blocks. In the afternoon, they would focus on performing tree maintenance and biowaste clean up. In the case of city events and the CBD – where bars and restaurants are located -or after a weekend, workers would focus on the area where the event took place and continue with their assigned activities. From the other side, private student accommodations, where around 30,000 students live, have their private collection in small trucks.

> *"So we haven't got to a point where there's a sort of a connected waste strategy for the full precinct" - CID*

The different collectors in the city take the gathered waste to five landfills where waste can be taken to. Usually, the waste goes to the closest landfill where collection occurs. In the case of the Hatfield study area, this is Hatherley Municipal Dumping Site located at 28.407°E - 25.741S. (**Figure** 12)

In the waste dumping sites, trucks dump their waste in the space indicated by the location supervisor. When the area is getting full is then compacted by a front-end loader. The waste dumping sites are open to the public, where they can discard materials such as construction waste, electrical appliances, or bio-degradable waste.

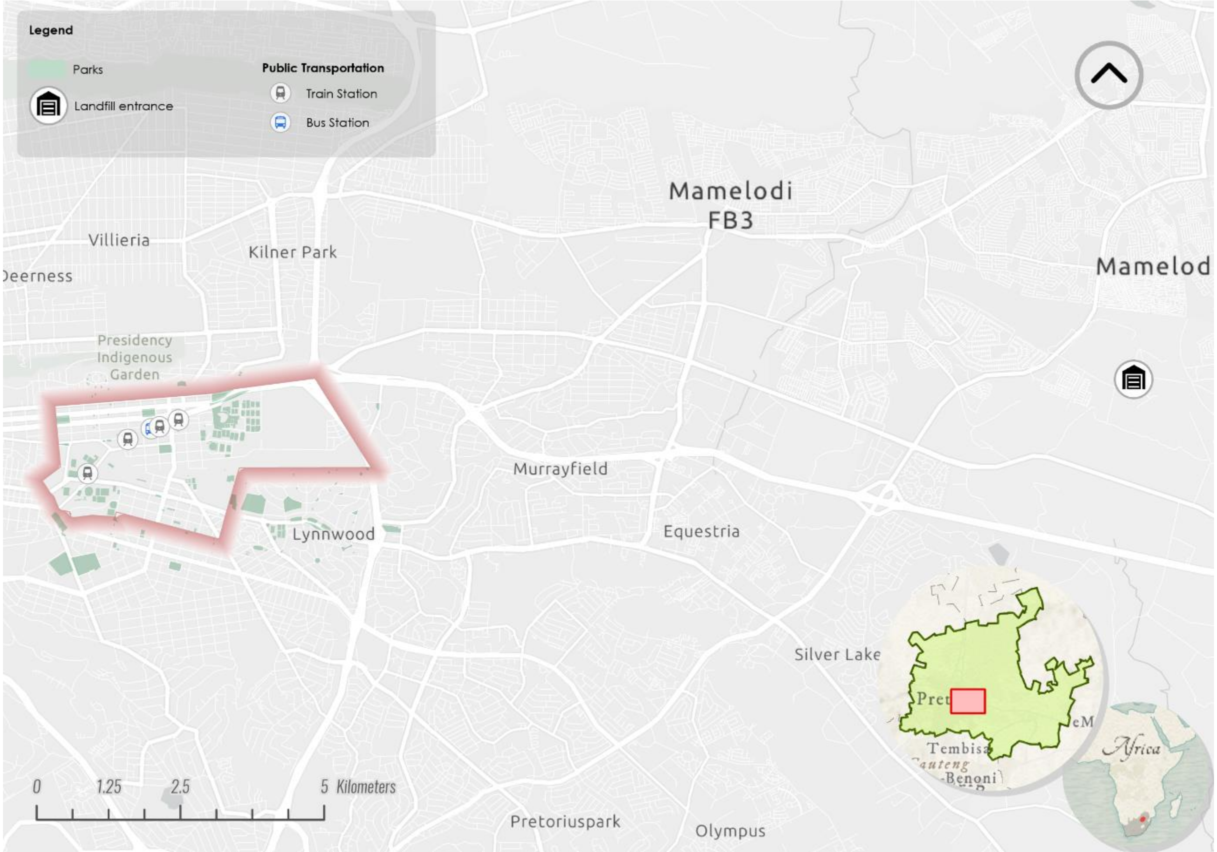

***Figure** 12. Hatherley Municipal Dumping Site location in relation to the Study Area*

5.1.2. Stakeholder Classification and System Requirements

A total of 15 stakeholders were identified after the stakeholders' workshop. Analyzing the workshop transcript, it was possible to create four pairwise comparison matrices for the four analysis attributes (See Annex 11.2) and classified in the typologies as seen in **Table** 6 and **Figure** 51 (see Annex). Three of them where identified as non-stakeholders for the Waste Digital Twin prototype: Local Researchers, Student residences and Composte providers.

***Table** 6. Stakeholders' attributes and typologies. Attribute values are percental weights for each attribute calculated. Bold numbers indicate the largest weight for each attribute, and blue numbers indicate the lowest weight for each attribute. Typologys highlighted in purple are the stakeholders considered a primary focus for compliance with user requirements.*

Stakeholder	Power	Urgency	Legitimacy	Proximity	Typology
Business and Offices	3.458	8.235	9.186	11.990	Expectant
Collection Companies	4.405	4.362	10.700	7.752	Claimant
Department of Forestry Fisheries and Environment	**27.949**	2.977	6.804	0.942	Dominant
Improvement District	8.740	**15.333**	9.168	9.306	Crucial
Industrial Parks	4.215	8.722	8.453	7.657	Expectant
Landfill Operators	7.830	2.304	2.245	2.817	Dormant
Municipality	18.560	13.637	10.394	4.071	Definitive
Real State Agencies	6.148	3.942	3.909	3.401	Dormant
Residents	4.572	11.305	**14.711**	**19.654**	Expectant
University Institution	5.699	12.589	10.738	7.313	Expectant
Ward councillor	7.020	14.911	11.017	11.112	Crucial
Waste picker	1.404	1.682	2.676	13.985	Recipient

The most powerful stakeholders are related to the political power the Department of Forestry Fisheries and Environment – DFFE - has on regulations and requirements for the provision of the solid waste management service. The regulations imposed lay on the municipality the responsibility for providing the service within their area or government, giving them the power to set up their own rules for service delivery.

Nonetheless, other stakeholders also have large power in solid waste management as the proximity to the core of waste management reduces. For instance, the landfill operators have gained non-overviewed control of the dumping sites where

> *"All […] points to a total lack of management from the city side. To control that (landfill operation) […] They (landfill operators) don't look too afraid to go there. All they're doing is: the trucks are being allowed in, and whatever happens there is being managed on site and the city keeps applied by, because they know each truck that comes in is already being paid."*

Apparently, this is due to the economic benefit it implies to operators at the cost of the citizens. As the municipality themselves recognizes:

> *"… it's not very good. [Waste] Generation is a lot of income from the city. The income, just by households and businesses pay them. They collect this waste in every place and go and then they dump it in about five landfills in the city."*

On the urgency side, the CID stakeholder has been identified as the one with more urgency as they provide a local governance service to the community who pay a tax to enhance the neighborhood. So, they want to deliver that promise and respond to the tax contributors. In their own words:

> *"We are friendly with the landlords. I mean they pay me a levy and we want to try and give them the most value for it. So, […] how do we make sure that we manage your waste in a more effective way because they [Business and Offices] waste everything in box street right? at the back of the center, and there's whatever serious smell there you understand? You know the bad smell is a sign of bad management. That's all it is. So, we need to find a better way of dealing with this thing and say: 'there's some clever people around the table who want to help you' because let's help each other in this thing so that for me is a very big opportunity."*

Another stakeholder identified with urgency is the Ward Councilor, as he becomes the key connection point between citizens and the municipality. Complaints of waste collection and littering go through the councilor, and their job gets filled with citizens' complaints when, for instance, waste has not been picked up, as the municipality representative recalls:

> *"[The] majority of ward councilors use WhatsApp systems very, very effectively. That's why [the] majority of ward councilors use WhatsApp systems very, very effectively. That's the shortest communication. Whether there's no water, no electricity, that poor council has been bombarded instantaneously. 'Why is electricity supposed to come on the level? It's now five minutes past 11, what does it mean?' The same request."*

The key informant also provides insights into how the councilor is this crucial link between communities and how they can benefit from the Digital Twin for waste management:

> *"So, when we are a problem as a domestic or business, and it's a big problem that I get frustrated with, I send my counsellor, and everybody does this, typically the first complaint. I also log my calls with the city to get a record, but usually the action happens through the WhatsApp group and the counsellor who elevates that issue. And that's how our cities function in a formal way."*

> *"… if we can advance whatever we're doing with waste and make that person shine and successful, that's a political massive value add on both sides of making waste go away or making crime, whatever the issue is. So, I think that's one of our end users. is can the ward councilor's job be so much easier and better because of how we are working with waste? That's a kind of end user."*

The legitimacy of the stakeholders is balanced between most of the stakeholders as each has its claim and is recognized by other stakeholders. However, residents become more legitimate as they are affected by the service performance and the effects illegal dumping can have. As the focus of the proposed Digital Twin is only on the collection phase of waste management, landfill operators were given low legitimacy compared to other stakeholders. This is also related to their interest in keeping waste flowing toward the landfill without much control, as explained above.

Finally, the proximity attribute was higher for the residents and waste pickers as they are in proximate contact with the waste, and any change in the waste management scheme will positively or negatively impact them. On the other hand, the DFFE has the least proximity to the stakeholders as their role is related to national policies and is more distant from local issues and solutions.

In this way, when organizing the stakeholders in the Salience Model, the CID and Ward councilor have a typology of Crucial as they rank high in all four attributes. The municipality is then characterized as a Definitive Stakeholder as it ranks high in three attributes but has lower proximity than other stakeholders. As explained in the methodology, as a result of the classification, these three stakeholders are the ones that were considered end-users of the Digital Twin tool. **Figure** 13 shows the distribution of the stakeholders on the sixteen possible typologies.

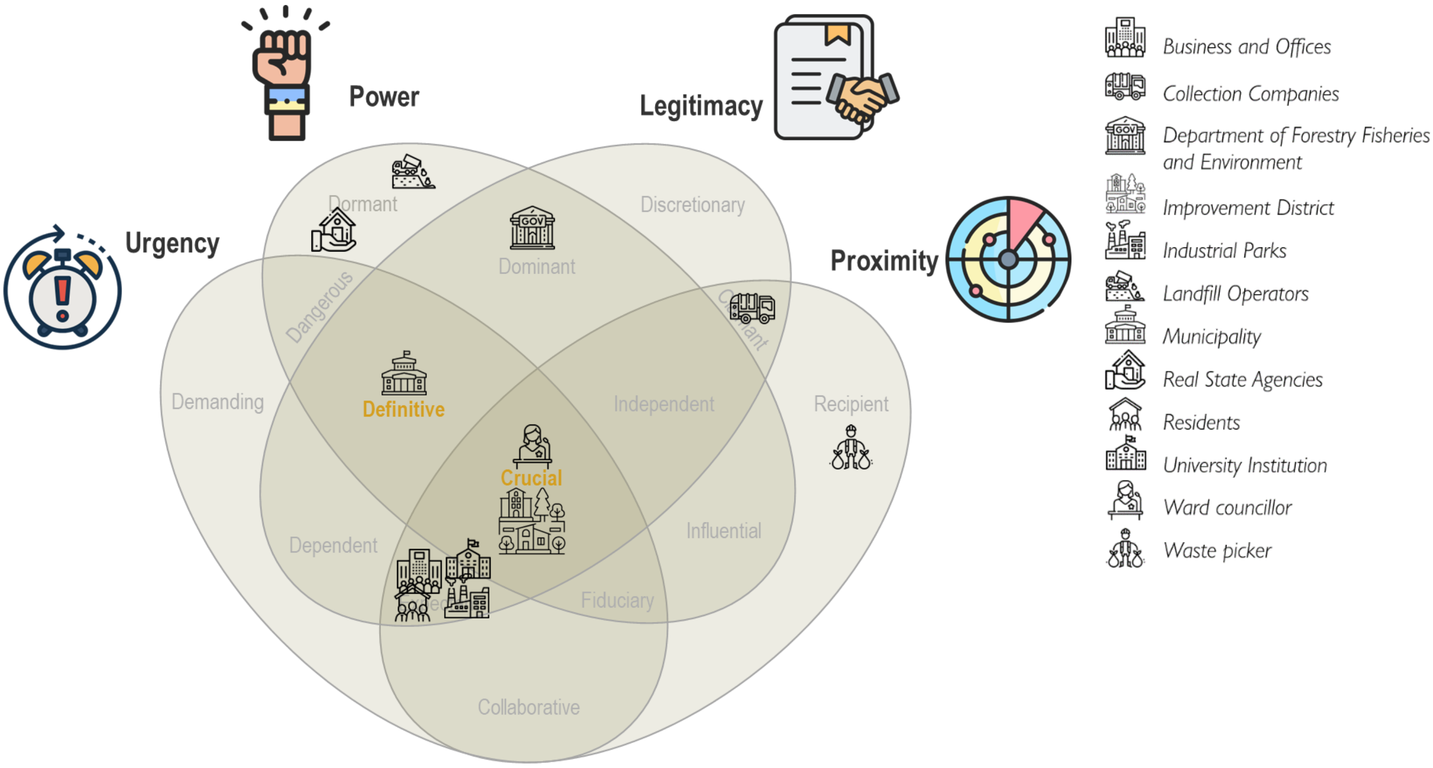

***Figure** 13. Stakeholders' typologies for Waste Collection Digital Twin.*

5.1.3. Stakeholders Requirements

The stakeholders identified 32 requirements for improving solid waste management: zero waste and assessing environmental impact, the most common. Stakeholders highlighted the importance of aligning to the Sustainable Development Goals (SDGs), the Nationally Determined Contributions (NDC) under the Paris Agreement, and the European Sustainability Reporting – ESG- Standards.

***Table** 7. Stakeholder user requirements.*

Category	Elements
Strategic	Carbon footprint reduction
	Environmental impact
	ESG reports
	Polluter Identification
	Reports to NDC for Paris Agreement
	Scalability to Country
	SDG Goals performance
	Sources of waste
	Type of waste generated
	Zero Waste
Performance	Dedicated person-hours
	Optimally used container's location

Category	Elements
	Recycling per building
	Recycling per campus (university)
	Recycling per sorting area
	Total Generation Waste
	Trucks Fuel consumption
	Waste production heatmaps
Operational	Container capacity level
	Container location
	Data Time series
	Emissions measurement (odors)
	Event preparations
	Historic accumulation of waste
	Optimal collection route
	Proportion and quantities that goes to landfill
	Real-time measurement
	Real-time generation
	Simple design
	Street sweepers distribution
	Visualization designed (also) for illiterate people
	Waste pickers distribution

According to the requirements urgency of the definitive and crucial stakeholders and recognizing time availability, resources, and external data that are not within the scope of the designed methodology, 17 of the requirements identified were not included in the final elements to be included in the Digital Twin. Even so, these requirements provide insightful information about all the elements different stakeholders would like to get information from and set a list of all the requirements that are needed for a complete development, at a city level, of a Waste Management Digital Twin that satisfies all stakeholder's requirements. The final requirements that were included are listed in **Table** 8.

Table *8. Final Requirements included in the Waste Management Digital Twin.*

Category	Elements
Strategic	Polluter Identification
	Scalability to Country
	SDG Goals performance
	(MSW Generated tons/d)
	Sources of waste
Performance	Optimally used container's location
	Total Generation Waste
	Trucks Fuel consumption
	Waste production heatmaps
Operational	Container capacity level
	Container location
	Optimal collection route
	Real-time production
	Simple design
	Visualization designed (also) for illiterate people

5.2. Data Collection

5.2.1. Solid Waste containers

The data collection results showed 2.236 reports. Of them, 3.04% were invalid, and 3.76% were inaccurate. A total of 1,270 containers in 1,151 locations were identified, with 4.16% reported as broken (see **Figure** 17 and **Figure** 14). Also, 136 ashtrays were identified inside the main campus and only one outside. It is important to highlight that during the collection process, students could not access the Industrial Park Located on the eastern side of the study area. Therefore, the waste management of this area was not considered in the design of the Digital Twin as it relates to private industrial gated areas.

Container volumes vary between 28 L and 10.58 m^3 on 67 different types of containers (**Figure** 15). The ones of 118 L are the most frequent, with 426 (33.54%) of the total recorded. This type of container corresponds to a standardized concrete or metal container (See **Figure** 16a and **Figure** 16**b**). Likewise, the containers 240L correspond to standard plastic movable containers (See **Figure** 16**c**), which are distributed to each home by the municipality as they help load waste to the waste collection trucks. The identified containers also include 25 dumpsters known as skips (see **Figure** 16**d**). These skips can be attached to collectors facilitating collection. The skips are loaded one at a time, compared to plastic containers collected in several bins in the same vehicle.

__Figure__ 14. Containers Distribution - Heatmap - in Study Area.

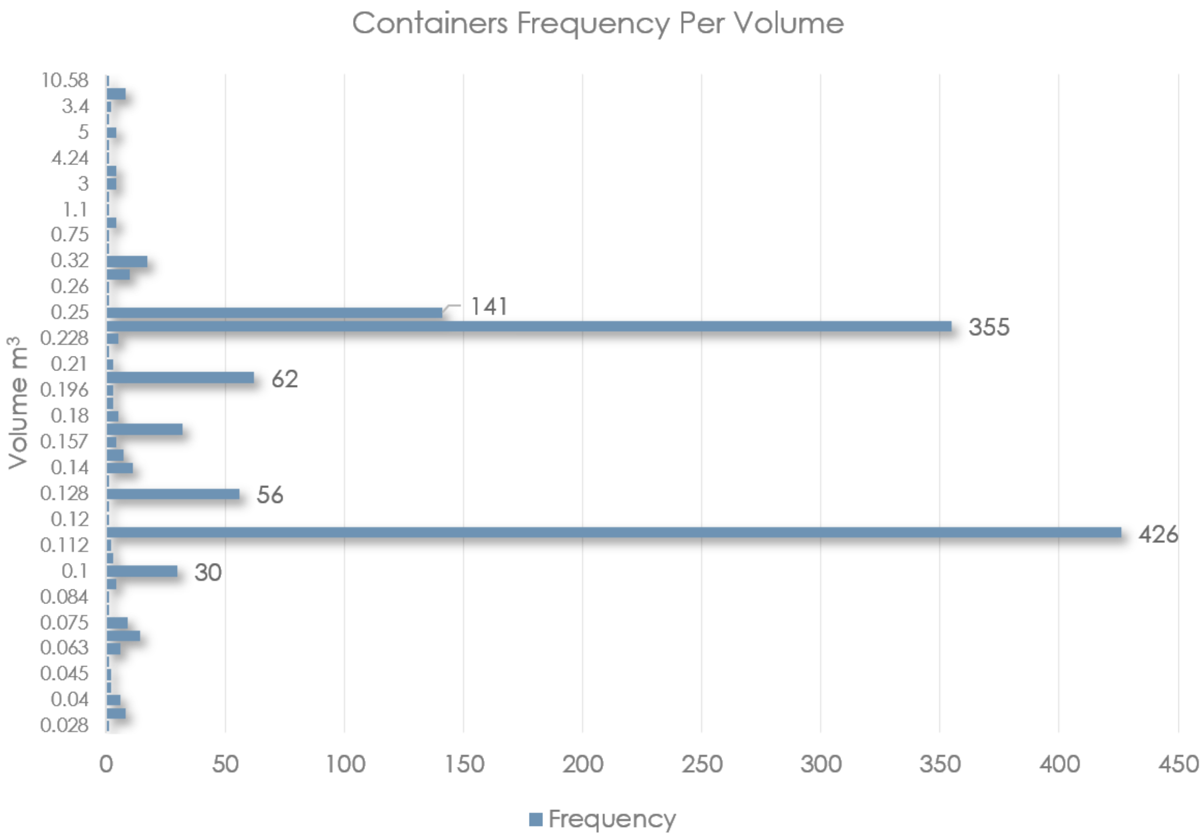

Figure *15. Containers' volume frequency distribution.*

Figure *16. Main observed type of containers. (a) Concrete 0.118 m³ (b) Metal 0.118 m³ (c) Plastic 0.240 m³ (d) Skip 4 m³*

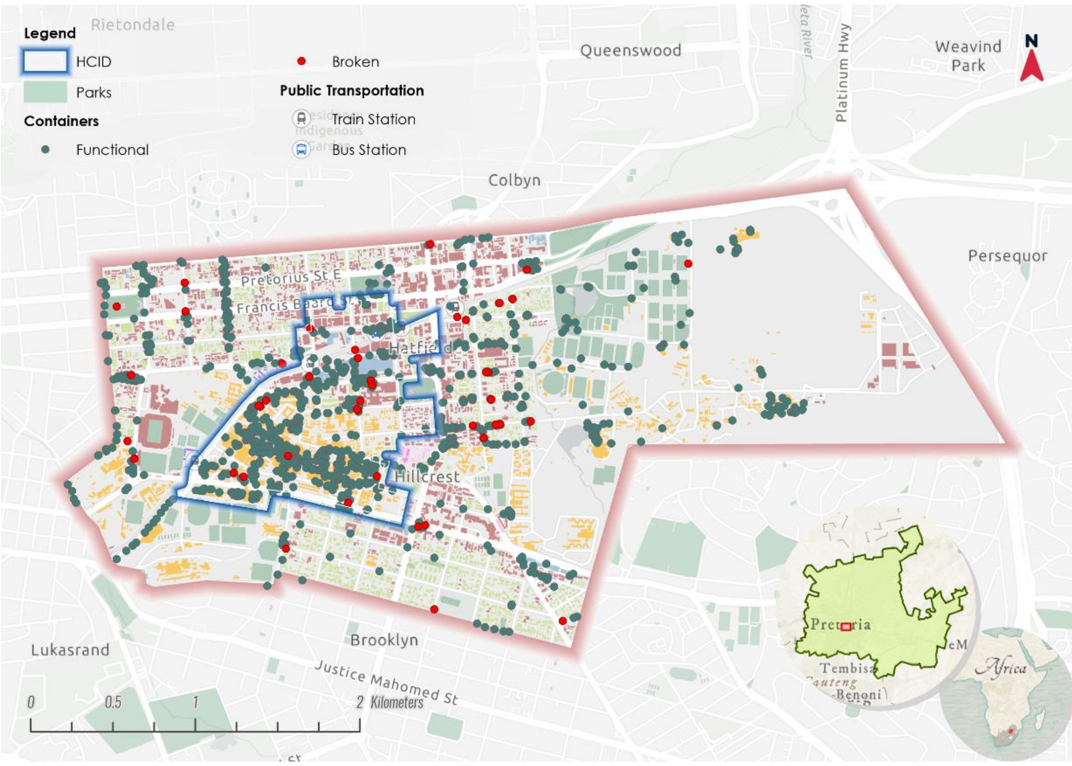

Figure 17. *Containers' location and functionality (Broken - Functional)*

Near-real-time monitoring of the reports allowed us to understand that containers were mainly located inside the UP campus and the Hatfield CID. On the live monitoring of the 02-March, it was possible to observe containers whose distribution obeyed to streets with their assigned collection on the same day data was collected. It relates to residential buildings and are not public containers. Their location and aggregation obey citizens taking their home containers into the street to be collected. (see blue points in **Figure** 18).

The data showed that public spaces do not have a good distribution of solid waste containers, as seen in areas where no record of solid waste containers was registered, as they correspond to exclusively residential areas in the North and South of the study area, such as the one between Hilda St. to Hill St. and Stanza Bopape St. to Arcadia St in the north, or between Murray St. to the M6 and William St. to Pienaar St. in the South (see **Figure** 19), that are outside the Hatfield CID.

Containers were aggregated based on a 25m distance, and values (number of containers and volume) were added. In this way, the 1,270 containers were reduced to 672 locations, with volumes ranging from 6.24 m^3 to 32 L (see **Figure** 20).

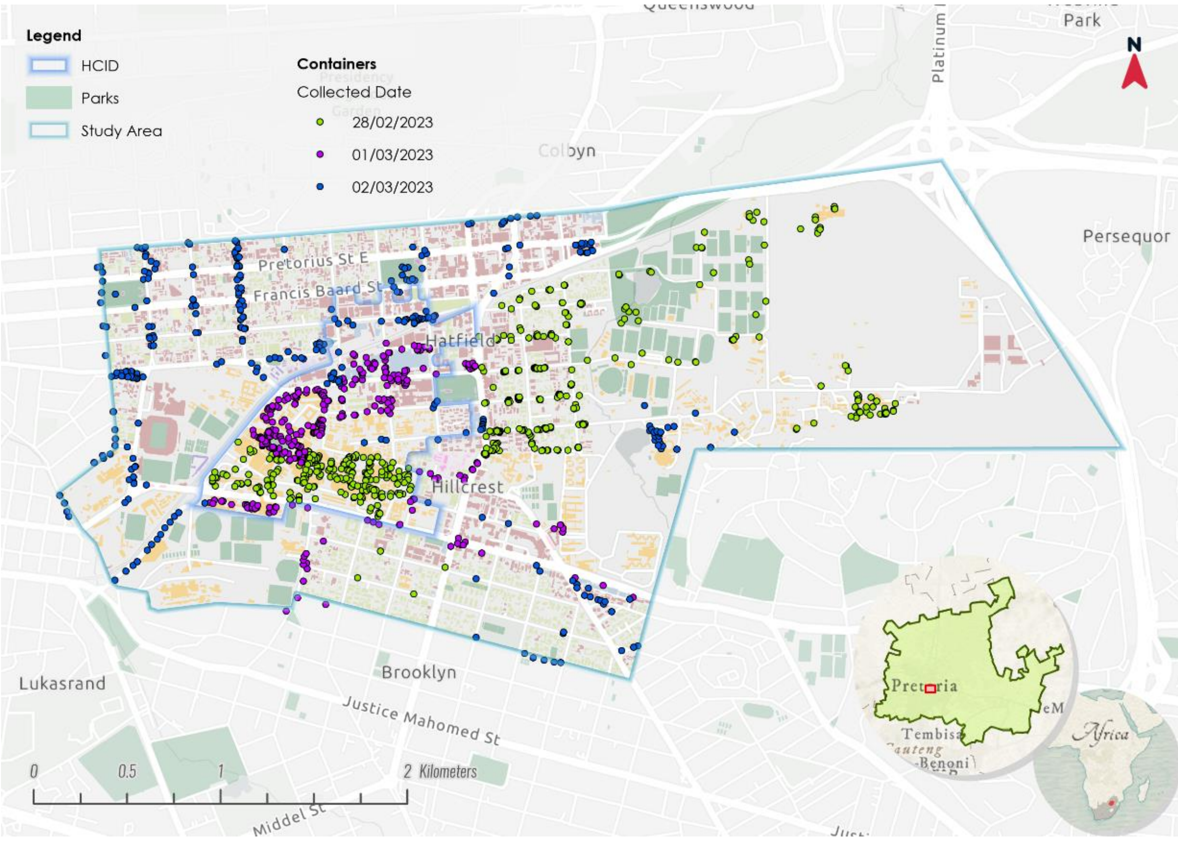

Figure 18. *Containers are grouped by the date of data collection.*

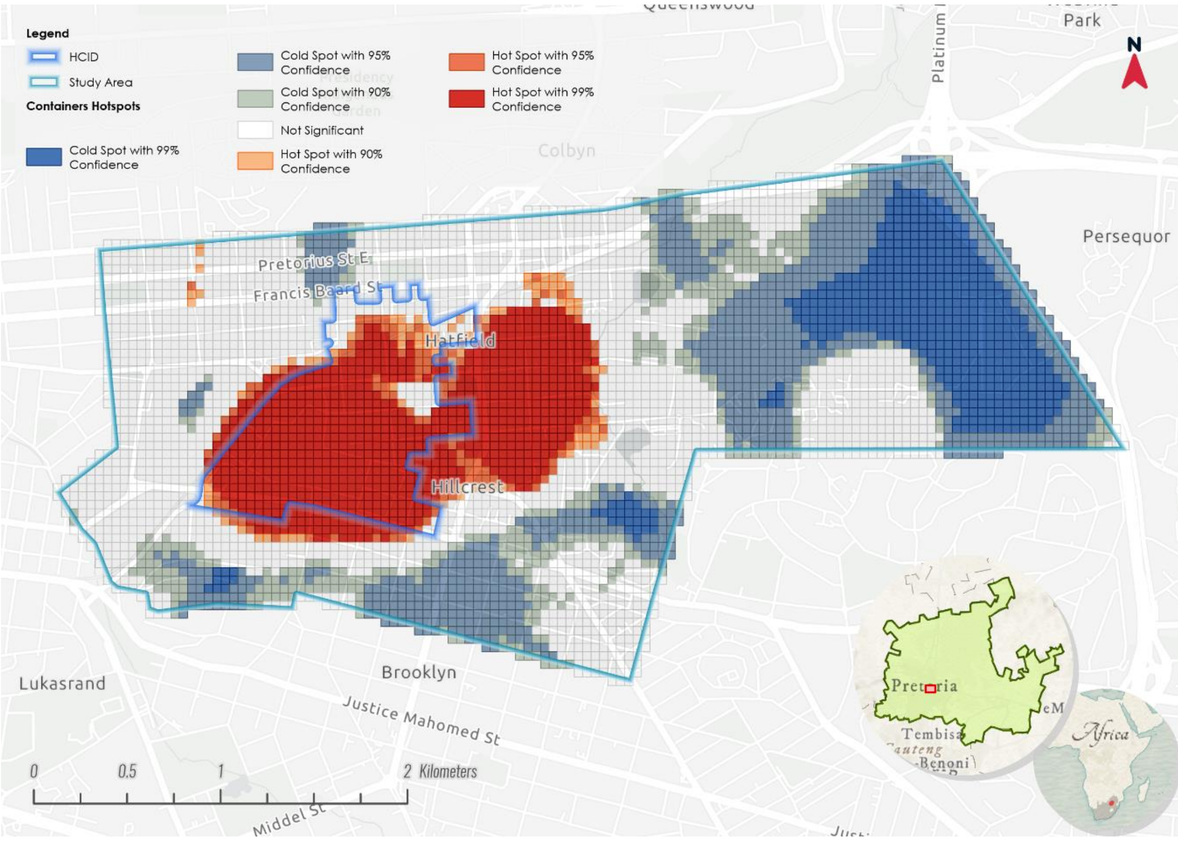

Figure 19. *Hotspot Analysis of container Distribution.*

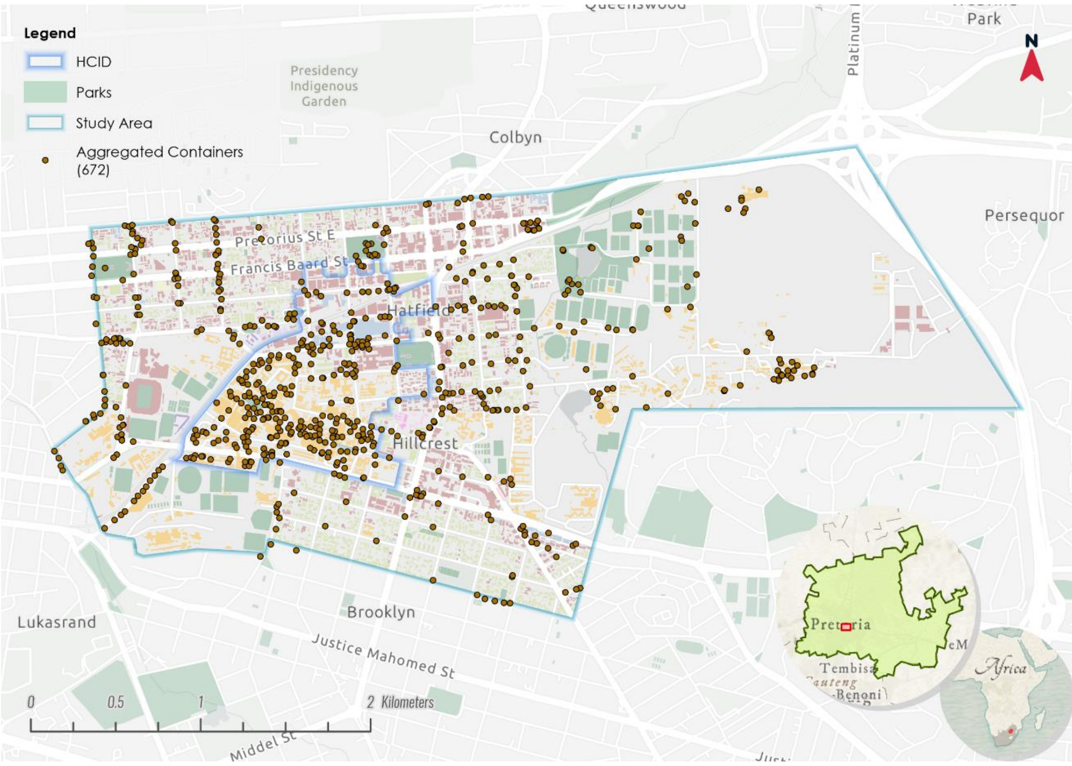

Figure 20. Aggregated Containers.

5.2.2. Littering Identification

On the illegal dumping and littering side, 820 reports were made and distributed in 593 minimal (72.3%), 176 moderate (21.5%), and 51 severe reports (6.2%) (see **Figure** 21). The main concentration of the reports was in the periphery of the parks, green areas, and playgrounds, such as Springbok Park and Hatfield Playpark, suggesting that the recreational and resting areas are common places for illegal dumping and require larger containers. Likewise, these parks show containers in the center of them and no containers in the periphery. Areas of the parks surrounding the container do have reports of litter.

The photographs taken by students to report on the illegal dumping show that areas underneath the trees are being used as the frequent place for littering, which adds up to the biowaste of tree maintenance and the natural accumulation of bark and leaves (see **Figure** 22). Some of the reports indicate that maintenance of green areas requires a rapid response from the collection company to avoid accumulation and attraction of other litter and disease vectors.

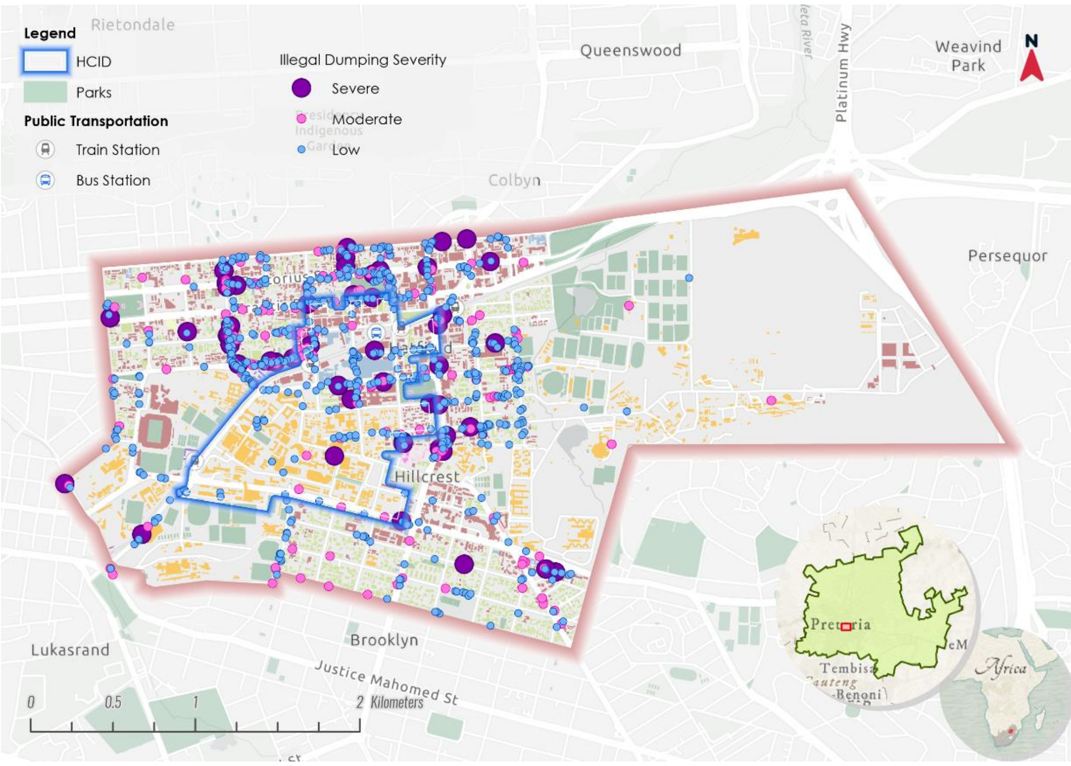

Figure 21. Illegal Dumping Severity and Distribution

***Figure** 22. Illegal dumping reports. (a) Event residues inside UP campus. (b) Car bumper disposed under a tree. (c) Littering under tree. (d) Biowaste, littering and illegal dumping under tree.*

5.3. Urban Waste Management Digital Twin Design

5.3.1. Building Identification

A total of 4,768 buildings were identified with the proposed method. The accuracy of it is shown in **Table** 9 based on a random 1,000 points allocation. After visual inspection, 663 polygons were eliminated as they correspond to trees, cars, car shades, and bushes.

***Table** 9. Confusion Matrix Building Identification.*

		Calculated State		
		Building	Non-Building	TOTAL
Actual State	Building	119	34	153
	Non-Building	14	833	847
	TOTAL	133	867	1000
	Positive Predicted Value			0.895
	False Omission Rate			0.039
	Accuracy			0.986

Students perform validation on 424 buildings (10.33%), focusing on residential areas. Those buildings' attributes were updated before 3D reconstruction and area calculation (see **Figure** 23). After validation, visual inspection of the Areal imagery, and using OSM data, 123 buildings could not be classified. The total number of buildings per class can be seen in **Figure** 25. Buildings classified as "Function" refer to parking lots, sheds, and garages. With the buildings identified and attributes corrected, the buildings were transformed into a 3D multipatch, as shown in **Figure** 24.

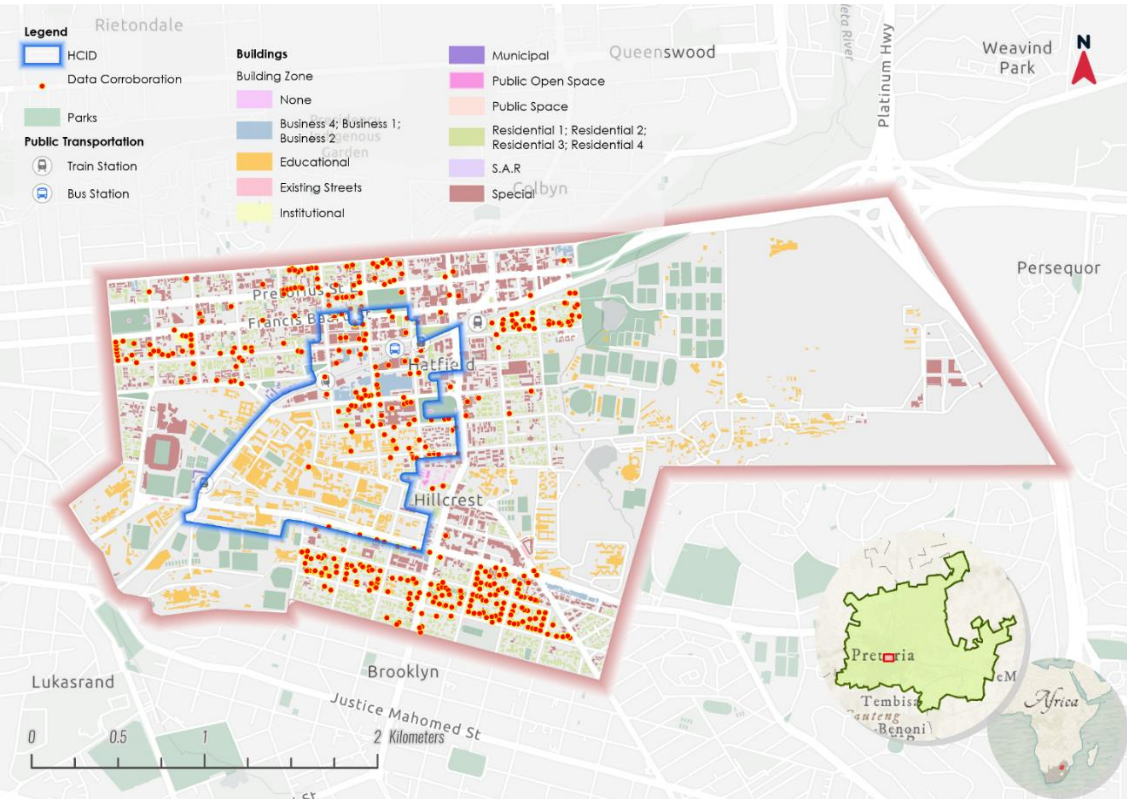

Figure 23. Data Corroboration on Building Attributes.

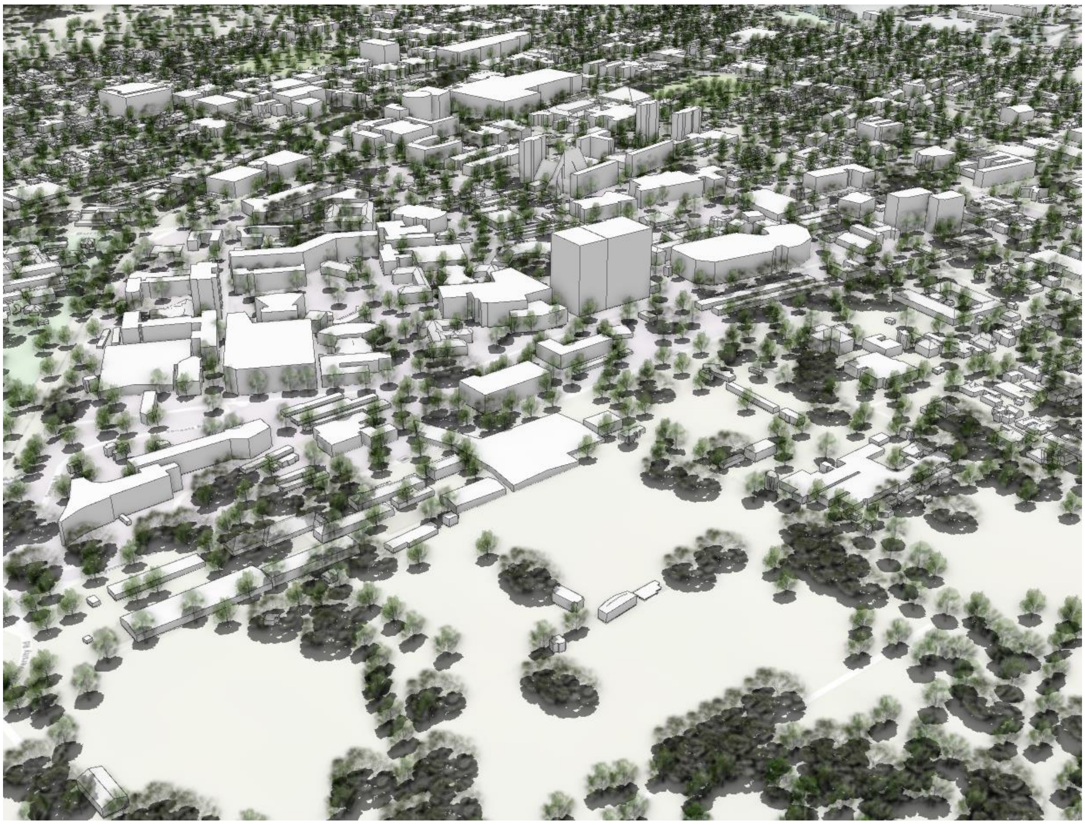

Figure 24. Study Area 3D Representation. Trees were extracted from LIDAR Scanning.

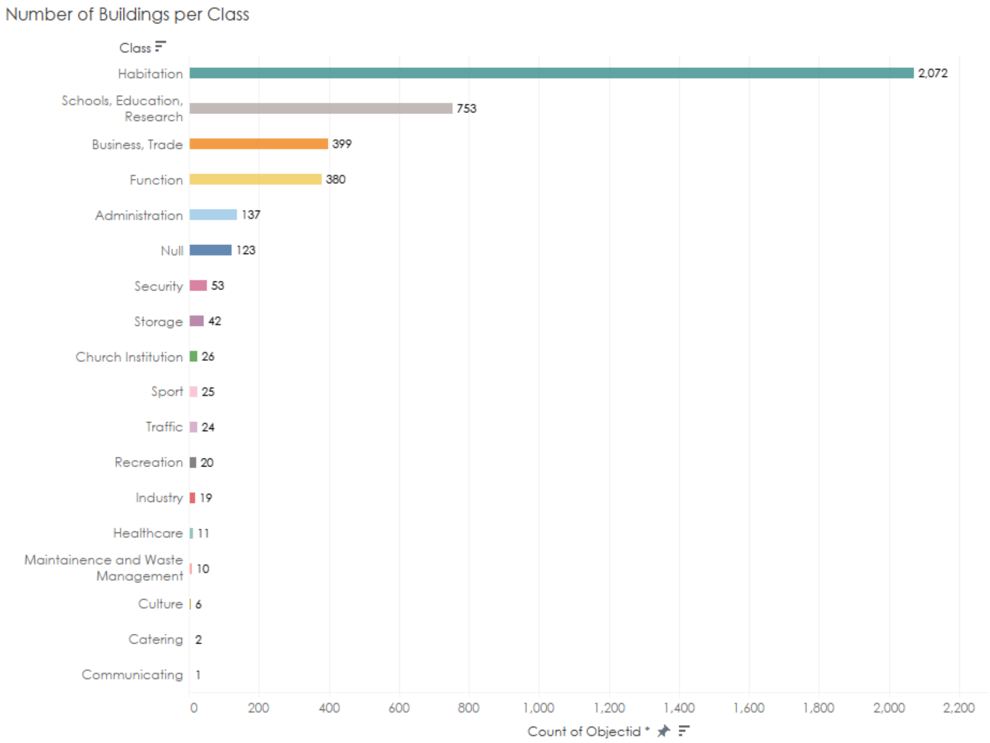

***Figure** 25. Number of Buildings per Class*

The building footprint area ranges from 3.5 m² (a small yet tall maintenance structure) to 25,885 m² (Loftus Stadium), where 3,506 buildings (85.4%) do not exceed 500 m². As seen in **Figure** 26, the area distribution per building class is consistent for each class, with only a few outliers. The aggregated footprint extent of the study area is 1,433,951.96 m² being habitational and school classes occupying more land (**Figure** 27).

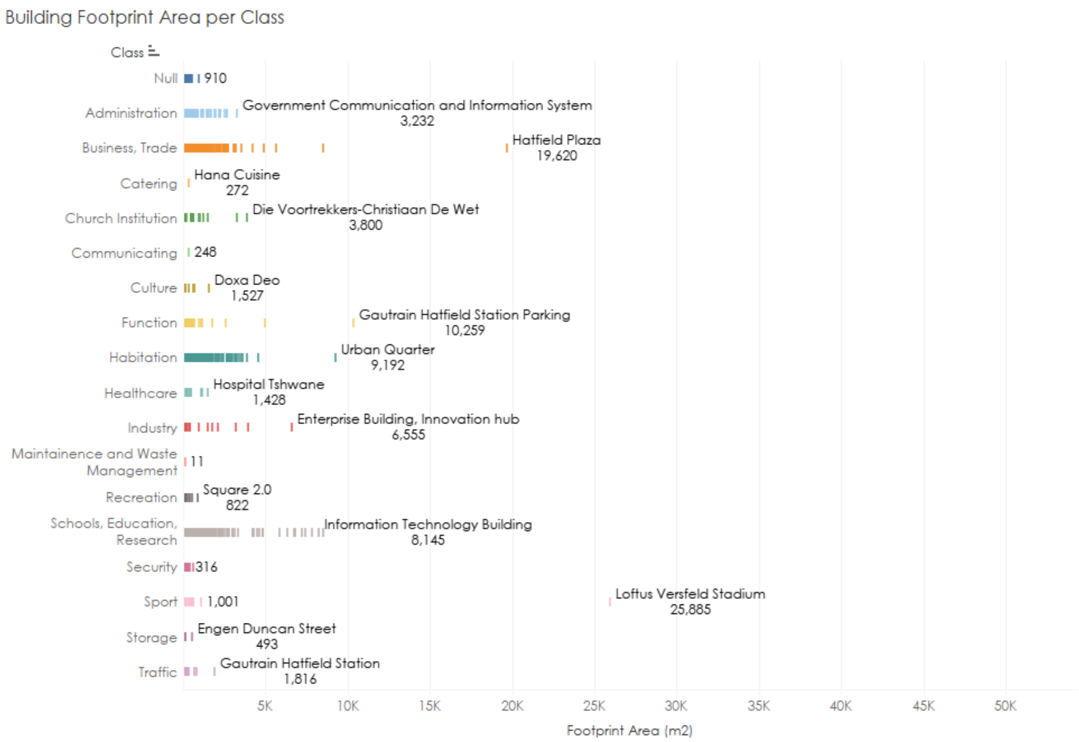

***Figure** 26. Building Footprint Area per building Class. For each class the largest building and its area is shown.*

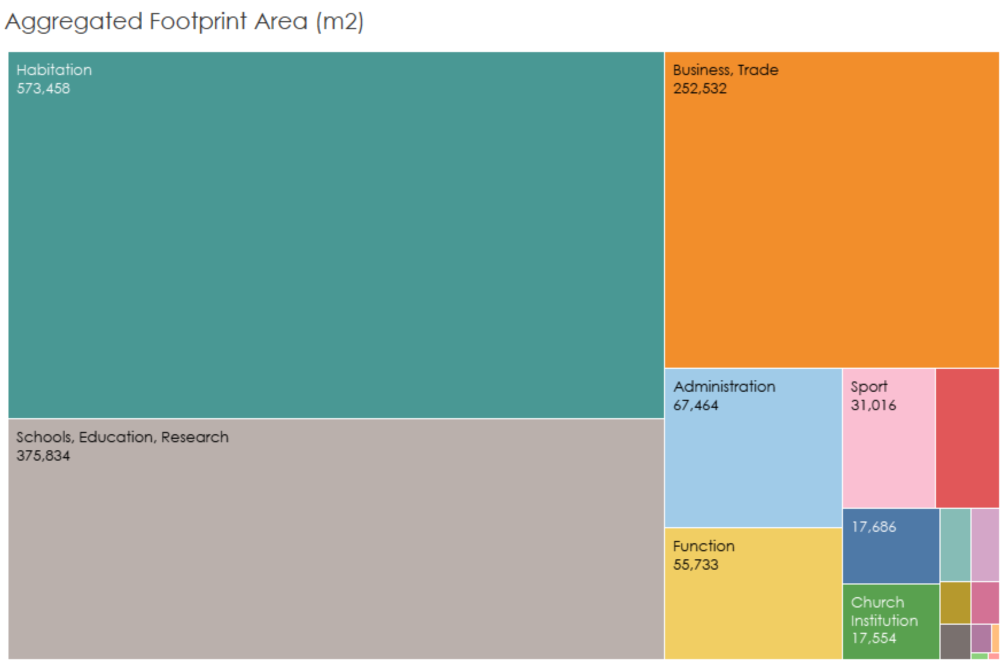

***Figure** 27. Aggregated Footprint Area distribution per building Class*

Figure 29 shows the distribution of the total footprint area. It ranges from 7m² (a security booth) to 336,510.36 m² (Loftus Stadium), and it is possible to observe that the buildings with larger floor areas are mainly located on the Hatfield CID. The aggregated footprint extent of the study area is 5,681,494.72 m², and habitational and school classes occupy the most extensive total floor area (**Figure** 28). It is possible to observe that function buildings occupy a large part of the overall area leaving the administrative ones in the sixth place of the total occupied area. This is due to the significant individual car dependency of the city and the several floors of parking lots that exist in the area, not including underground parking.

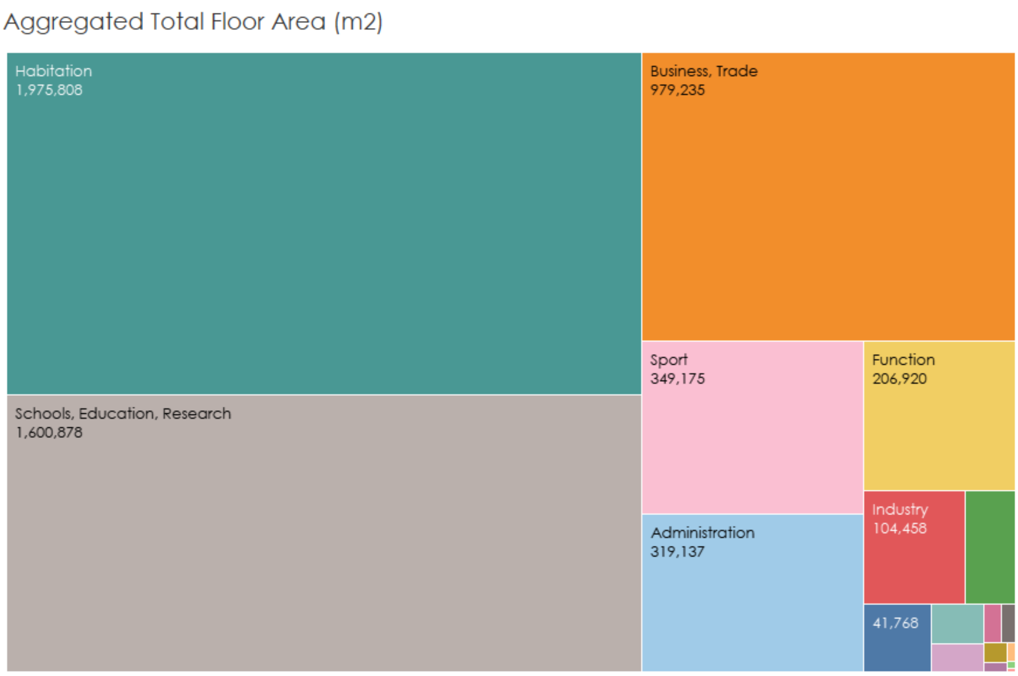

***Figure** 28. Aggregated Total Floor area per building class.*

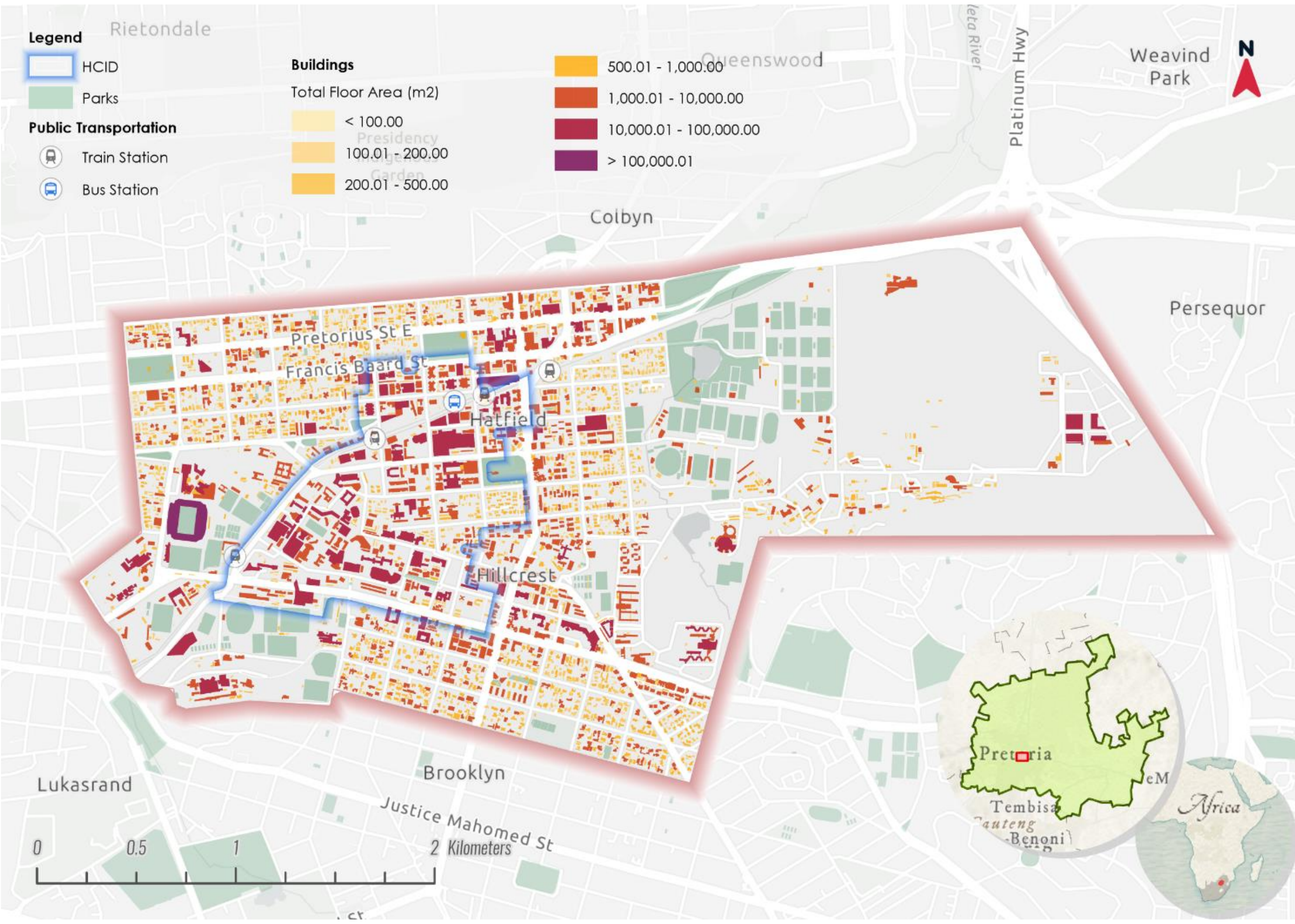

Figure 29. Buildings Total Floor Area (m2)

5.3.2. Solid Waste Generation

The buildings were assigned to the closest container as shown in **Figure** 30. The maximum distance that a building is assigned is 881.80 m which implies a walk of 14 minutes (calculated at 1m/s walking speed). This large distance corresponds to the buildings located on the industrial park, which were not accessible on data collection. It is possible that some closer containers exist or that each building has its own container inside the manufacturing facilities.

Excluding the industrial buildings, the longest distance of assignation is 427.40m, a walk of 7.1 minutes. The average distance from building to container is on non-industrial buildings is 86.08 m with a median of 72.51 m and a standard deviation of 58.16m. The minimum distance from a building to a container is 2.51m. **Figure** 31 shows the distribution of the calculated distances for all buildings.

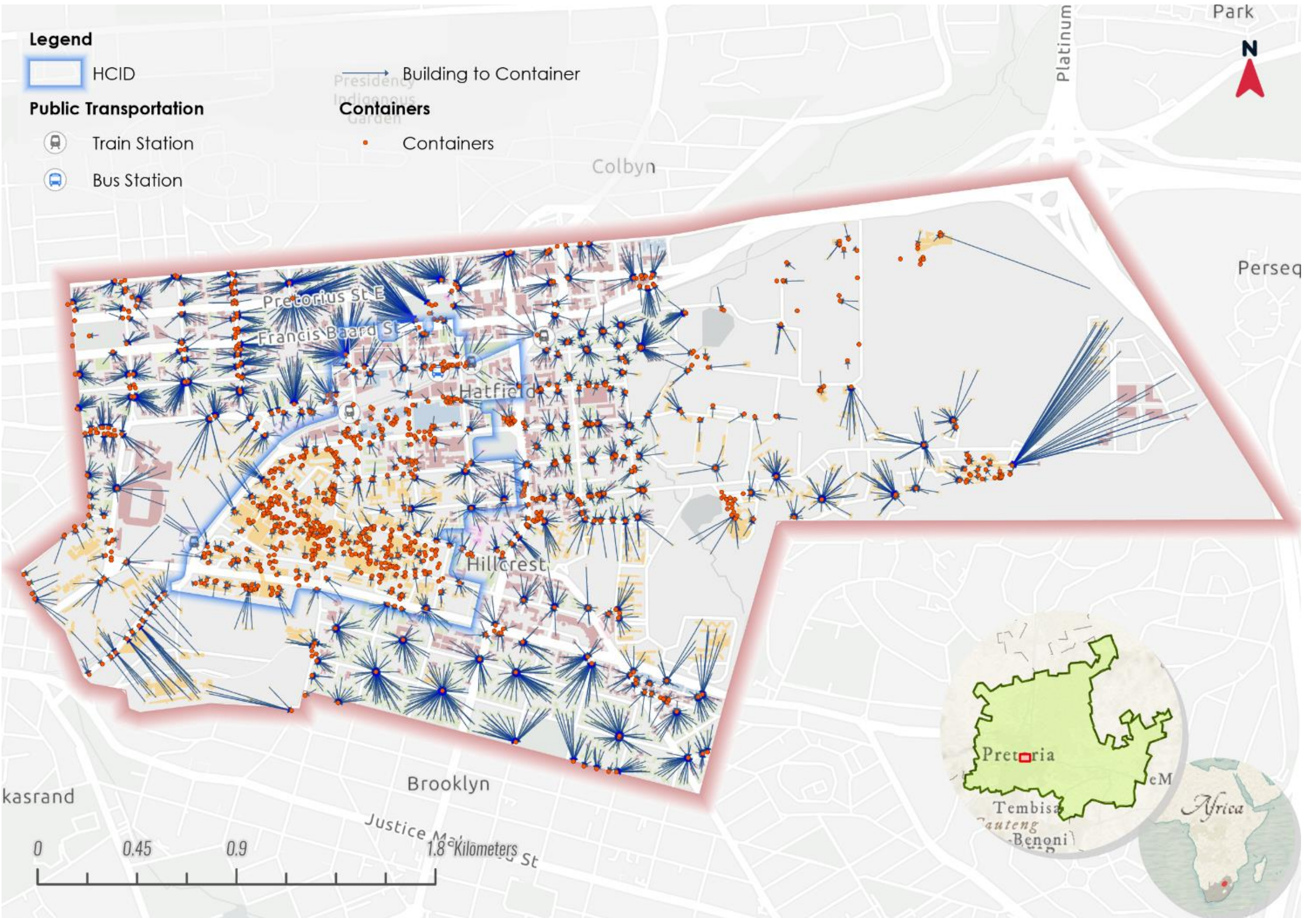

Figure 30. Building to Container Assignation map.

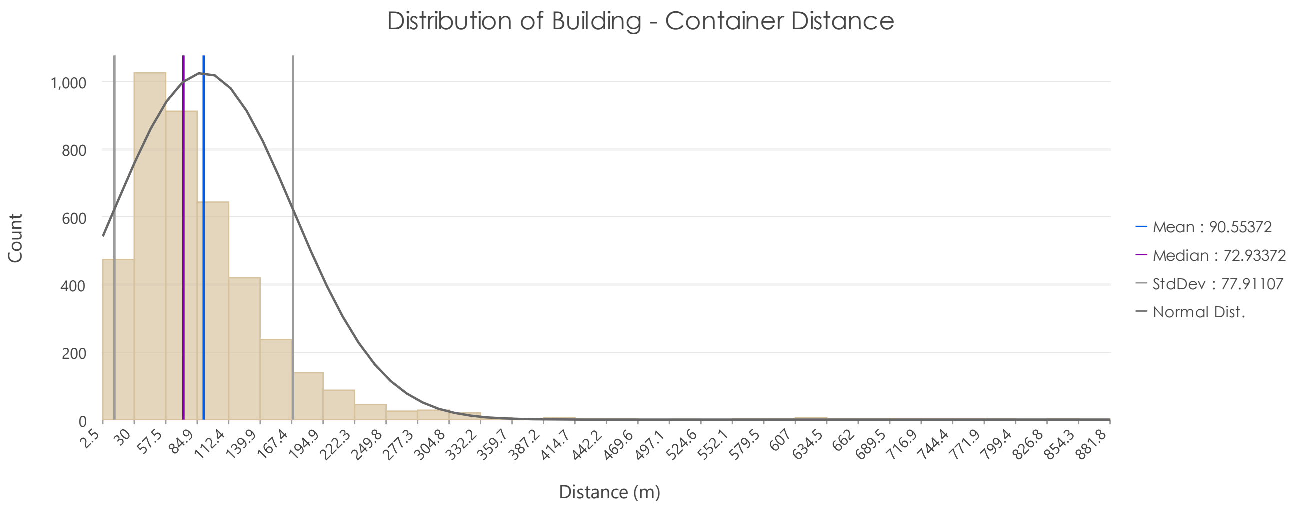

Figure 31. Distribution of Building to Container distances in meters.

The calculated residential buildings' waste production ranges between 0 kg/d and 1,575.60 kg/d, with an average of 11.19 kg/d. Due to the method used to calculate the number of inhabitants on each building, and the low population density on each 100x100m grid, there are 662 (31.95%) buildings with no residents and, therefore, no waste production. Even with this gap in the waste estimation, the calculated values for residential buildings add up to 23.12 tons of waste produced daily.

For the non-residential buildings category D have the greatest number of buildings (see **Figure** 32). Nonetheless, the largest production relates to Category C, which includes the Stadium, with a total production of 251.81 tons per day. Category A has only 73 buildings, but their waste production sums up to 149.83 tons per day.

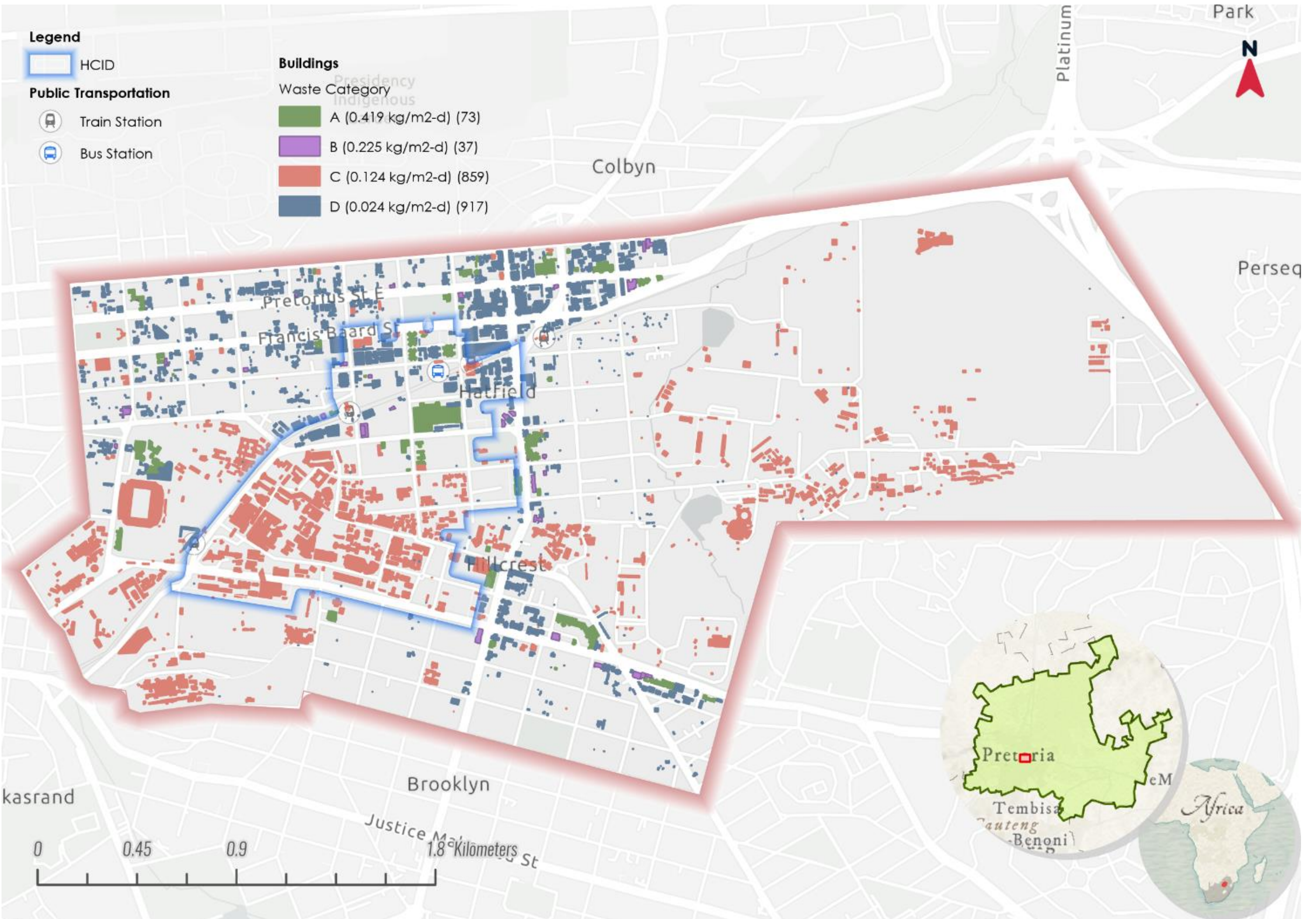

***Figure** 32. Building Classification per Waste Category*

According to the calculations, the largest waste producers are the educational buildings, 198.51 tons per day (42.64%), and the Business and commercial buildings, which produce 170 tons per day (36.58%). Overall, the largest producers of waste are Loftus Versfeld Stadium (41.72 tons per day), Hatfield Plaza (41.10 tons per day), Hillcrest Boulevard Shopping Center (17.71 tons per day), and the Information Technology Building of UP (8.08 tons per day). In **Table** 10 and **Table** 11 is possible to observe the distribution of waste production for both building class and category.

***Table** 10. Waste production per Building Class*

Building Class	Total Waste Production (kg/d)	MAX per Building (kg/d)	MIN per Building (kg/d)	Average (kg/d)	Std. Dev.
Administration	7,659.30	930.72	0.94	55.91	109.87
Business, Trade	170,274.35	41,103.38	0.70	426.75	2,380.45
Catering	313.81	252.64	61.17	156.90	135.39
Church Institution	6,451.07	1,413.50	1.62	248.12	341.20
Communicating	11.92	11.92	11.92	11.92	-
Culture	537.37	189.29	8.75	89.56	81.30
Function	4,966.08	2,462.11	0.22	13.03	129.02
Habitation	23,115.30	1,575.60	0.00	11.19	56.60
Healthcare	7,933.26	3,589.41	45.96	721.21	1,115.65
Maintenance and Waste Management	6.82	3.14	0.17	0.68	0.87

Building Class	Total Waste Production (kg/d)	MAX per Building (kg/d)	MIN per Building (kg/d)	Average (kg/d)	Std. Dev.
Recreation	622.32	203.79	1.16	31.12	51.82
Schools, Education, Research	198,508.92	8,079.84	1.37	263.62	740.11
Security	146.67	28.02	0.17	2.77	5.77
Sport	43,297.64	41,727.28	1.68	1,665.29	8,171.57
Storage	45.24	11.82	0.18	1.08	1.92
Traffic	1,615.76	900.73	0.00	67.32	185.97
TOTAL	**465,505.82**	**41,727.28**	**0.00**	**117.64**	**1,068.68**

***Table** 11. Waste Production per Building Category*

Building Category	Total Waste Production (kg/d)	MAX per Building (kg/d)	MIN per Building (kg/d)	Average (kg/d)	Std. Dev.
A	149,828.77	41,103.38	27.72	2,052.45	5,301.89
B	14,169.03	1,531.37	5.00	382.95	425.22
C	251,811.20	41,727.28	1.16	293.14	1,578.39
D	26,581.51	2,462.11	0.17	28.99	106.64
TOTAL	**442,390.52**	**41,727.28**	**0.17**	**234.57**	**1,538.57**

After values are assigned to containers is possible to directly observe the disproportionate waste generated compared to the capacity of containers. **Figure** 33 compares each container's daily waste generation and capacity, where 413 (61.46%) have enough capacity for daily waste production. The other containers have an average exceedance of 1,660.23%, with a median of 526.02% and a standard deviation of 3,901.98%. The distribution of containers with good capacity and those with low capacity are visible in

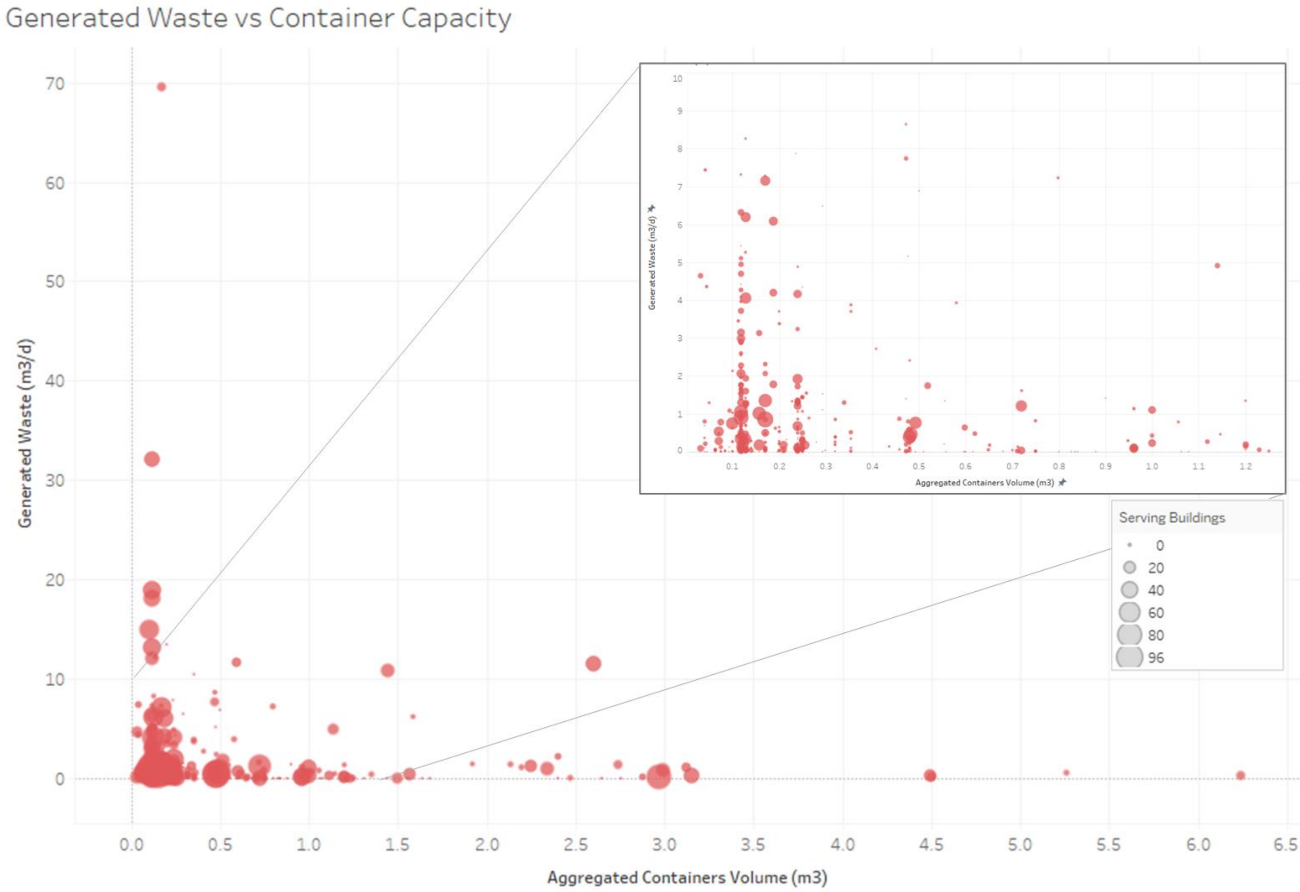

***Figure** 33. Daily Generated Waste vs. Containers Capacity*

5.3.3. Generation Simulation

Considering this production and simulating hourly waste generation from each building, the simulations can show the status of containers on each step of the analysis, i.e., every hour. **Figure** 34 through **Figure** 37 show how such simulations are generated before calculating an optimal route. Here it is possible to observe that 18 containers are saturated at the beginning of simulated hour 1, indicating suboptimal use of such containers and the need for allocating higher capacity to the area. At simulated hour 6, when containers are set to be collected, the number of bins is 116, with a total volume of 56.5 tons. As waste generation is simulated randomly, within the expected generation of waste per day of each building, values and location variate from one to another simulation. Nonetheless, areas close to the stadium, inside the UP, and in proximity to the Train station show that they require constant collection to avoid overflow of the containers.

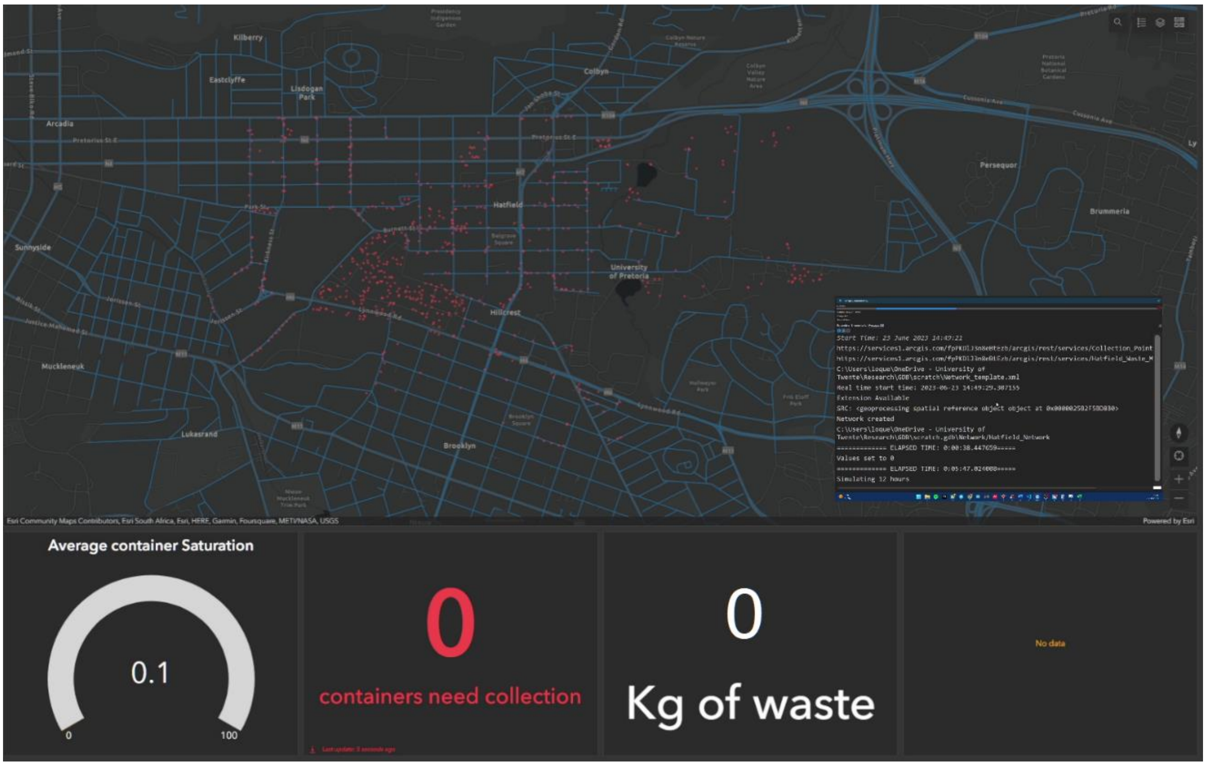

***Figure** 34. Waste Generation Simulation - Initial State.*

***Figure** 35. Waste Generation Simulation - Hour 1.*

***Figure** 36. Waste Generation Simulation - Hour 3.*

***Figure** 37. Waste Generation Simulation - Hour 6, step before route calculation.* *[Demo Video]*

5.3.4. Optimal Collection Routes

The road network analyzed has 2,792 edges where speed variates from 40 km/h in residential areas to 120 km/h in highways (see **Figure** 38). Segment lengths vary from 9 cm to 2.97 km with a median value of 160.39 m and a standard deviation of 239.56 m (See **Figure** 39). On these edges, the time (weight) also varies from 0.25 ms (9cm segment) to 2.97 min with a standard deviation of 12.92 seconds (see **Figure** 40). As one of the major restrictions for the transit of vehicles from and to the landfill, a total of 1,572 (56.30%) edges were identified as unidirectional. These road segments are mainly located inside the study area and correspond to local roads, while peripheral highways and arterial roads are of type bidirectional, as seen in **Figure** 41.

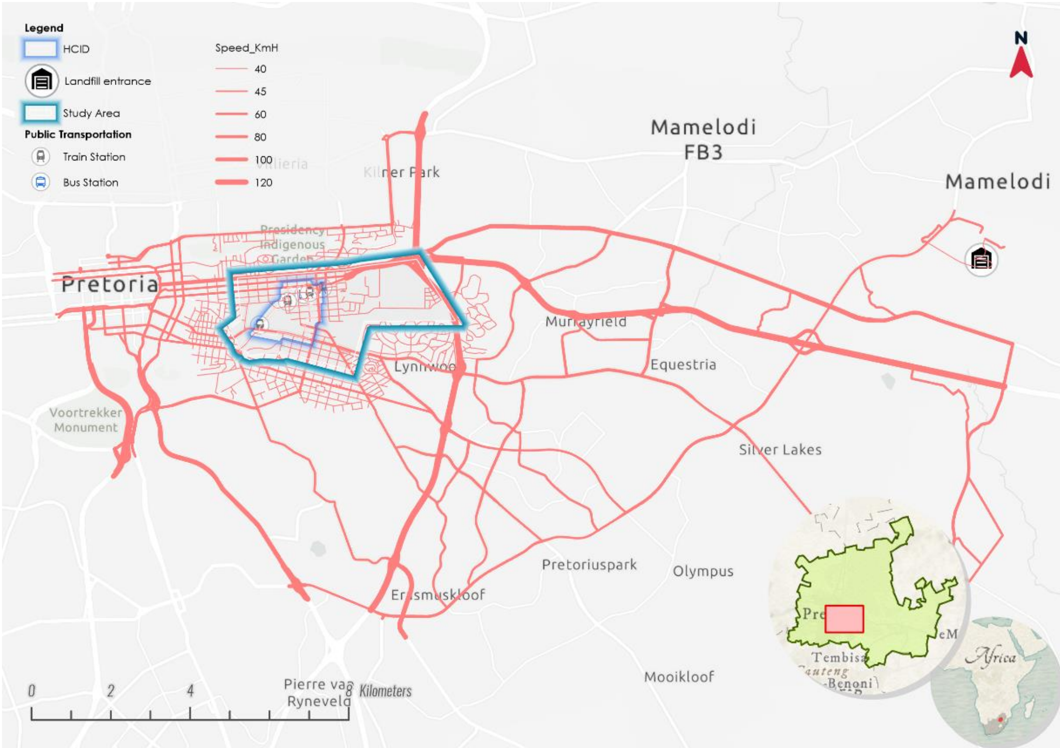

Figure 38. Roads speed from Landfill to Study Area

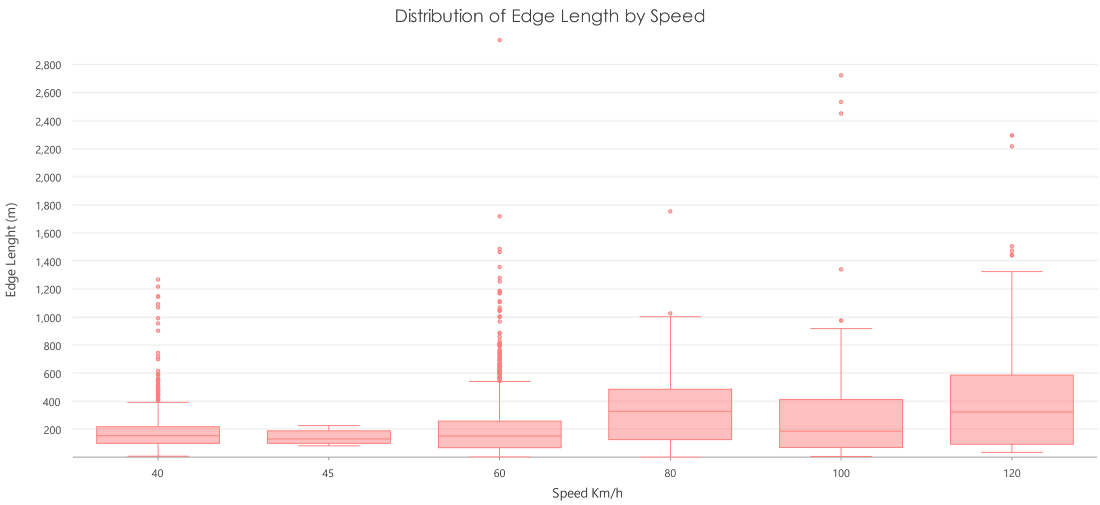

Figure 39. Distribution of Edges Length by Speed type.

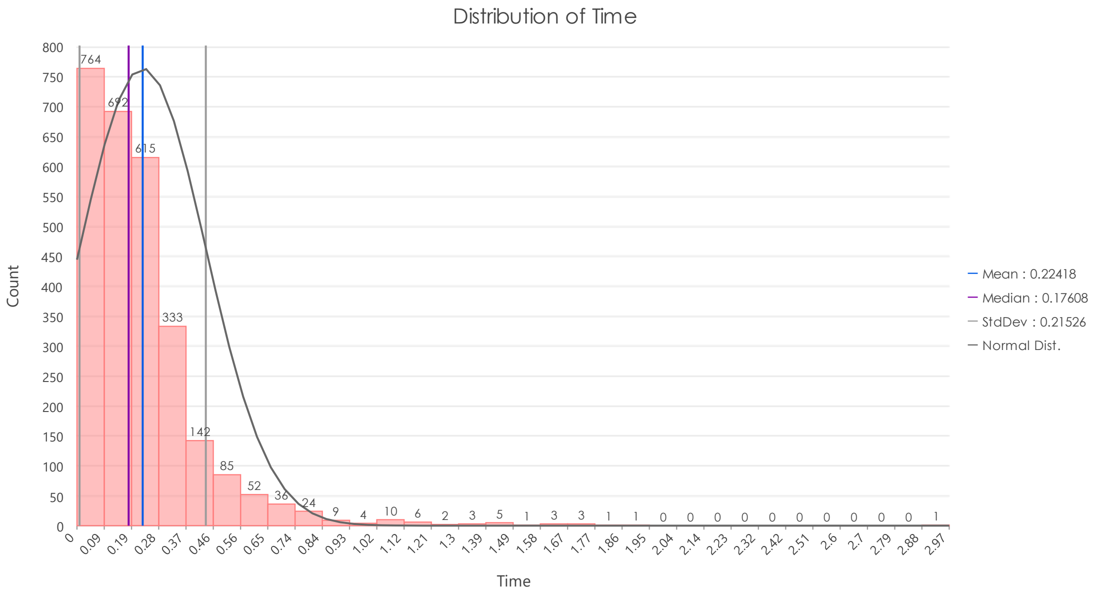

Figure 40. Distribution of Time (weight) to travel each road segment (edge)

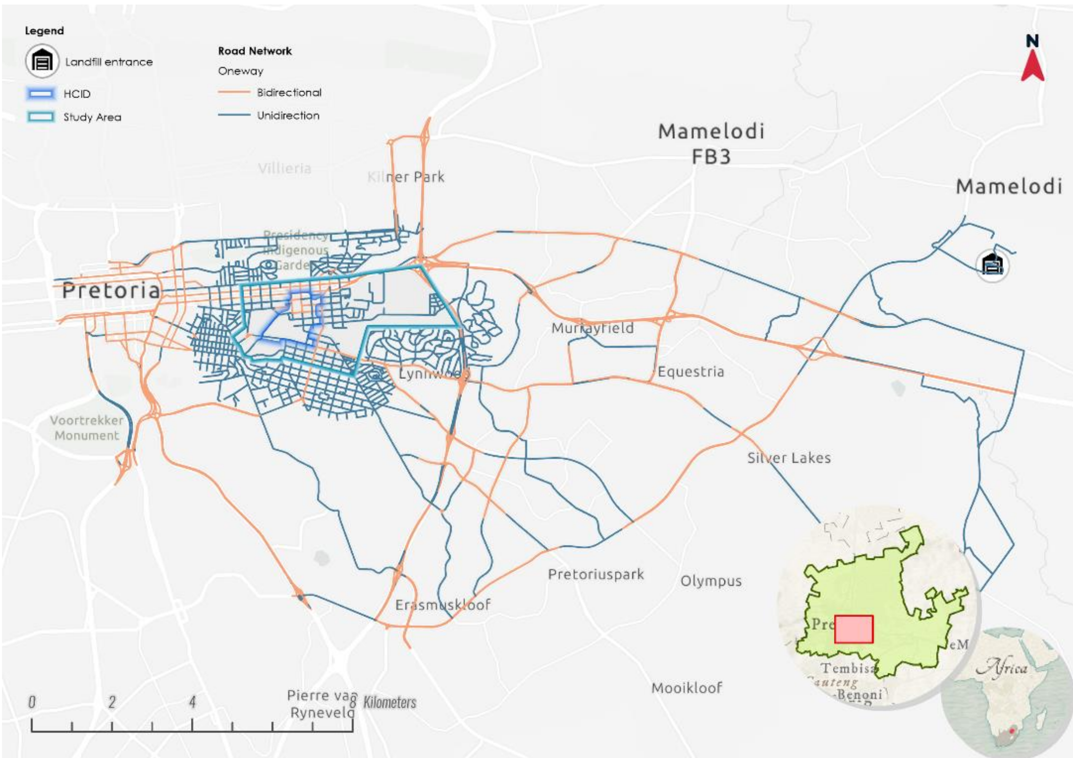

Figure 41. Type of Roads Map, Bidirectional or Unidirectional classification.

Due to the large production of the Stadium and the fact that this building does not operate daily, it was excluded from the optimal route calculation. The large production of the building and not having a specific container for its large production, which is located inside the building and not in the public area, would generate miscalculations, and the routing of trucks would concentrate on only collecting such waste.

A route, as shown in **Figure** 42, is generated when performing the simulations for waste collection along with step-by-step navigation directions (**Figure** 43). After simulating several hours, multiple paths that trucks follow each day are observed (**Figure** 44); however, some locations are repeated as there is constant waste overflow (**Figure** 45), just as expected from the results of the waste calculation.

On each route, the expected number of containers to collect varies from 112 to 213. In the majority of the routes, vehicles requiere four visits to the landfill to discharge waste and perform all contianer collection. However, the interval of waste generation goes from 6 hours to 12 hours, it is necessary to perfrom 9 visits to the landfill. The average time of collection is 5 hours and 16 minutes on a 6 hour generation period. And 10 hours and 57 minutes for a 12 hours generation period. The total travelled distance per each route averages at 236.28 km which translates into 1,327 ZAR (69.70 USD) and 2.73 Tons of CO_2 per route (calculated at 11.59kg/km (EPA, 2023)).

Figure 42. Optimal Route Example. The route includes returns to the landfill to dump waste and restart capacity.

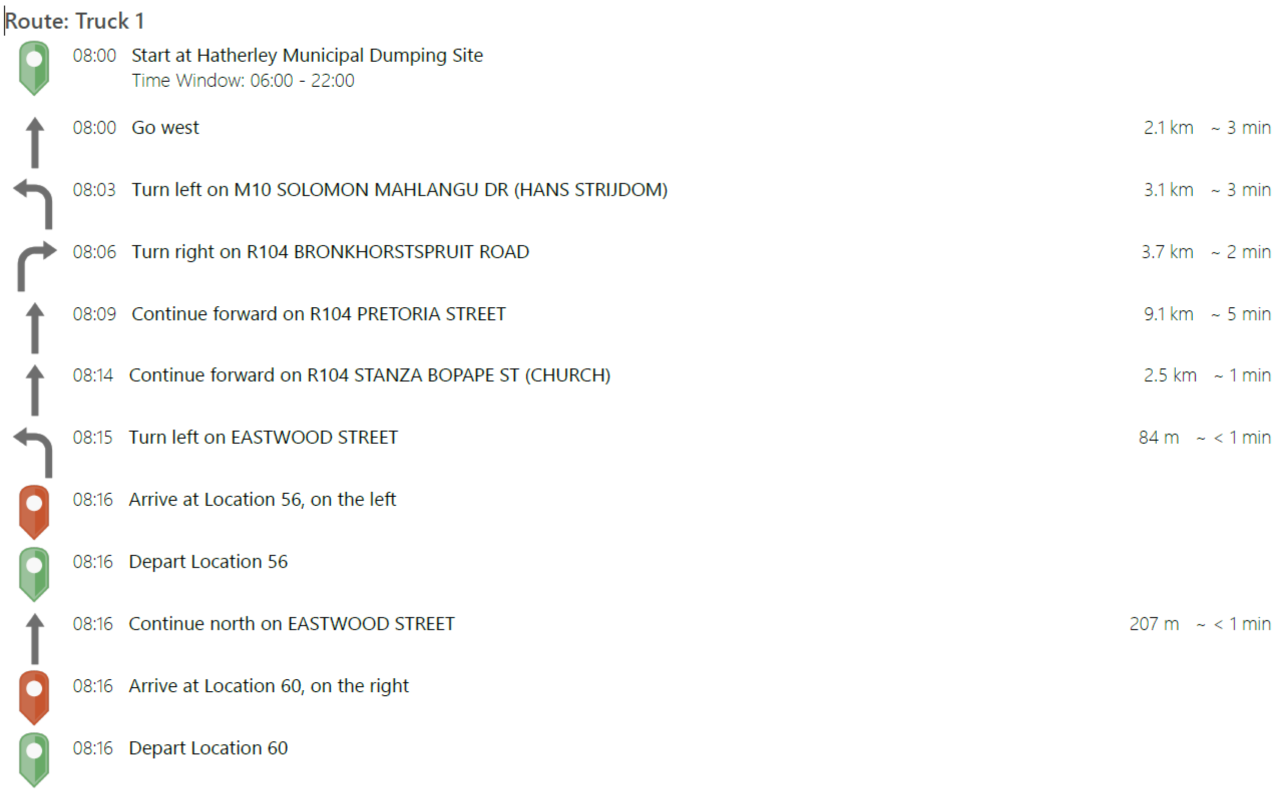

Figure 43. *Step-by-step directions generated on Optimal route calculation.*

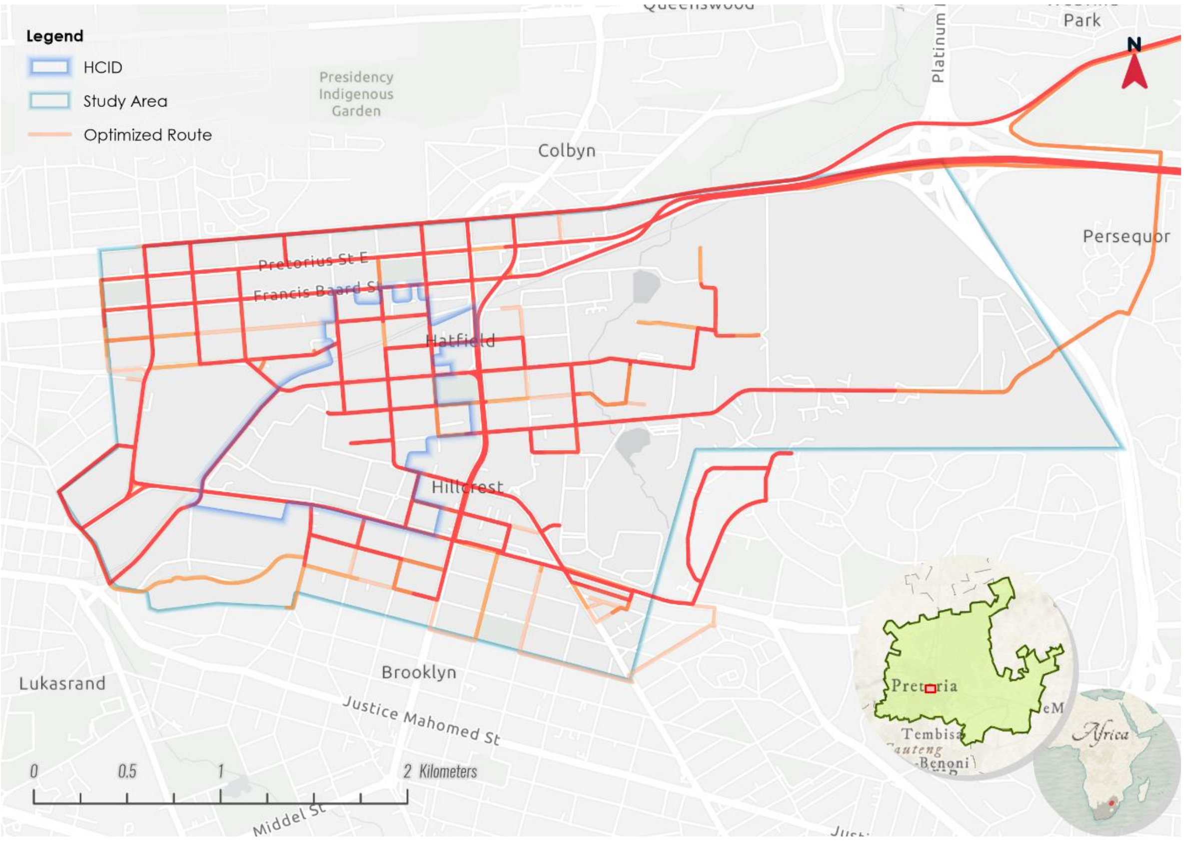

Figure 44. *Multiple paths for waste collection. Darker colors indicate several travels on the same street segment.*

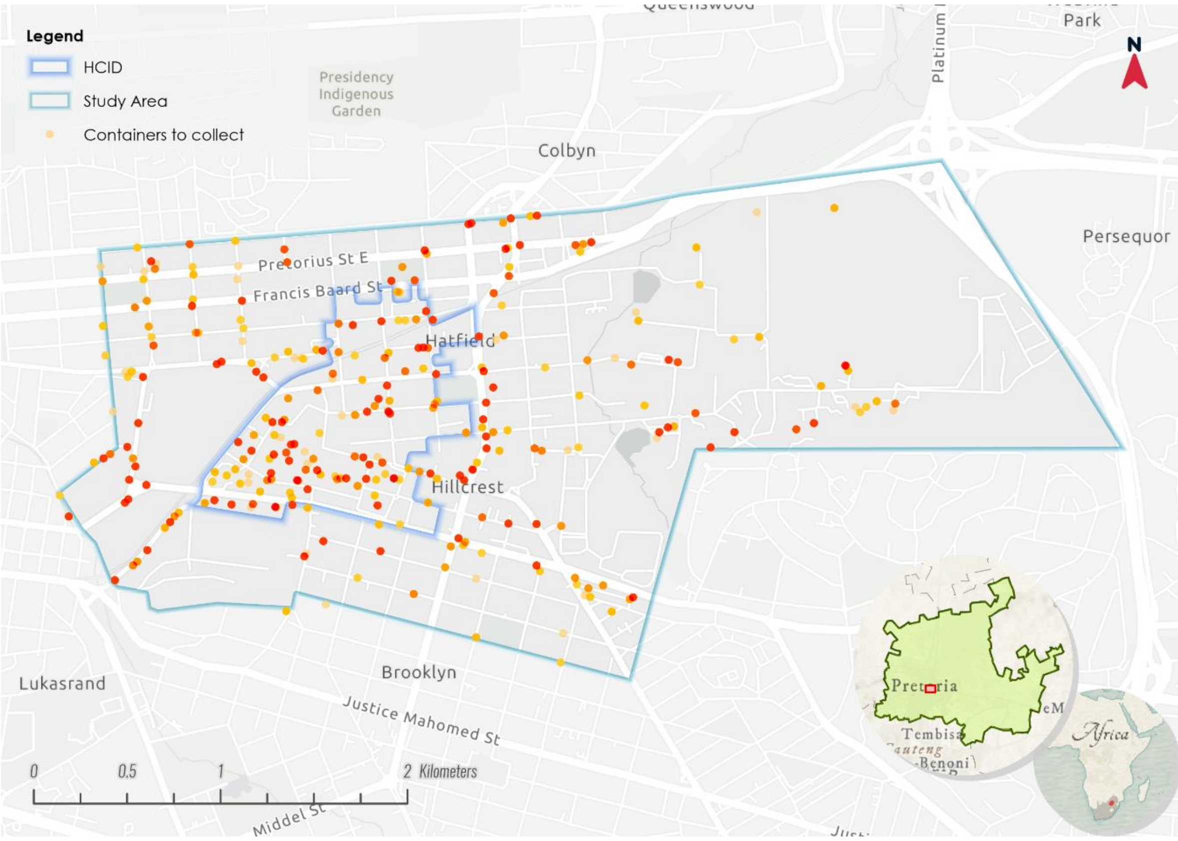

***Figure** 45. Containers to collect. Darker colors indicate several collections required on the same container.*

5.3.5. Dashboard Design

A centralized control dashboard was created using ArcGIS Dashboards[3] to visualize elements of the digital twin. The design focused on making map views of the central items and indicators that operate with the state of each map layer. The map view includes three options for visualization. The first option (**Figure** 46) focuses on the containers and the collection optimization. Here containers that need to be collected are highlighted on the map, and the collection sequence is displayed along the collection route. This dynamic map adapts to real-time container saturation and waste accumulation value modification.

The second option focuses on buildings where it is possible to visualize the class of each building and how each of them relates to a container. This view allows the user to understand the local distribution of waste and the distance required to move from each building to a container hub. (See **Figure** 47). The third option relates to the tracking of waste littering. Here, a heatmap of the reports made during the data collection phase is displayed (see **Figure** 48), and filtering options are available to highlight the different severity of litter.

[3] https://www.esri.com/en-us/arcgis/products/arcgis-dashboards/overview

Figure 46. Containers collection Route Map - Dashboard option 1

Figure 47. Buildings to containers assignation Map - Dashboard option 2

***Figure** 48. Illegal Dumping Reports Map - Dashboard option 3*

Following the requirements identified in Phase I, eleven indicators are displayed on the dashboard (**Figure** 46 and **Figure** 47)). The first two indicators focus on the saturation of the containers, where it is possible to observe the average saturation of containers and the number of containers to be collected. The third indicator relates to map option three, where littering reports are visualized in a pie chart categorized by severity.

The fourth indicator displays the total waste in the study area and needs to be collected regardless of the saturation of the containers. This indicator relates to the SDG 11 monitoring (Total Solid waste production per day). On indicator 5, it is possible to read the total volume of waste production per building class, an indicator that relates to map option 2. This indicator is not dynamic as it relates to building characteristics and estimated inhabitants.

Indicators 6 to 11 relate to the waste collection route showing critical elements for planning such as Fuel cost, CO_2 emissions, Total traveled distance, Total operation time, number of required returns to landfill (after the truck's capacity is complete), and a list of the sequence of collection for the containers. This sequence is interactive, and by activating each element of the series, items are highlighted in map option 1.

Figure 49. *Dashboard and indicators (signaled on yellow brackets)*

Figure 50. *Dashboard and indicators (signaled on yellow brackets)*

5.4. Waste Digital Twin Assessment

5.4.1. Simulations Performance

The speed performance of the simulation variates between local and cloud ran services. Running the tool in a local setup, with a computer of 28 GB RAM, 3.8 GHz - 8 cores – 16 threads CPU, and 4 GB dedicated GPU takes an average of 5.02 seconds for each hour of waste generation calculation and 2.72 minutes for calculating the optimal collection routes. On the other hand, when moving to a Cloud service, using an ArcGIS server with 64 GB RAM, 2.1 GHz - 8 cores – 16 threads CPU, and no GPU, the process of each simulated hour moves to 4.18 minutes (a 4,996% increase) and the optimal route calculation extends to 4.93 minutes (a 181% increase).

This is due to the structure of the process where online stored layers require downloading records, making one record update, and immediately updating the tuples to the layer instead of updating all tuples at once at the end of each run.

5.4.2. Stakeholders Assessment

The survey had a response rate of 38.1% (8/21), with one of the respondents unable to access the dashboard. This respondent's answer was discarded from the analysis. Overall, the dashboard obtained high scores, with only Data accuracy and Decision-making support indicator scoring under 4 points. Here, 28.57% do not consider that the dashboard efficiently conveys the waste quantity in the containers and waste generation per building and do not consider that the dashboard represents container saturation. Therefore, the communicative value of the dashboard needs to be improved, making it more straightforward into the waste state per container and how waste is generated from building to container. On the other hand, 85.71% of respondents give a 5-point score to the dashboard as a tool that provides information for collaboration and addresses waste management challenges. **Table** 12 shows each indicator's scores and the average for the different categories.

Table *12. Dashboard survey Score based on a 5-point Likert scale.*

Category	Indicator	Score	Category Score
User Friendliness and Interactivity	Ease of Use	4.48	4.27
	Data Exploration	4.05	
Spatial Interface	Map Visualization	4.52	4.43
Interactivity	Ease of Learning	4.33	
Consensus, Effectiveness and Communicative Value	Data Accuracy and Decision-making Support	3.93	4.11
	Stakeholder Communication and Collaboration	4.29	

The low response rate does not make this result reliable. However, during an open conversation at the end of the workshop, there were some insights from the stakeholders on the usefulness and communicative value of the tool. For instance, for the municipality is not clear the objective of the tool:

> *"What's the value and how can a municipality use your tool besides just playing around? Officials like to have toys inside, just have a nice GIS tool. But how can this really assist the city or waste department to optimize their collection?"* – Municipality Officer

This indicates that engagement with stakeholders and the explanation of the tool was not assertive. The purpose and goals of the Digital Twin were not adequately communicated so that stakeholders could embrace the tool and know what could be done with it.

From another perspective, Hatfield CID found that this twin can show their work's added value in the public space as they can visualize their impact related to solid waste management:

> *"If I look at the heat map, it would appear that the areas around us is in a lot worse state than the area that you're currently managing. I'll take the kudos from my cleaning team, which I love a lot. […] It shows that the effort that we're putting in to manage the waste in the CID area is actually making an impact. And as I said, the heat map, I always say that data don't lie if you use it truthfully. So people can see that we are making a positive impact." – Hatfield CID*

On the private side, Industrial parks Stakeholder highlight one limitation of the routing approach and that is related to restricted areas. This is, roads inside private property and containers inside the restricted access area. As there was no available data about access restrictions, it was impossible to consider this within the model, which would need to be improved for future work.

Residents praise the data accessibility and the information provided without having deep knowledge of GIS software. They emphasize that the approach allows students, planners, and architects to access and use the information. However, they stress that it is required to create a particular kind of incentive for citizens to engage in reporting and “prompt people to get involved and take their time to contribute data to this twin.” On the design, residents indicate that the dark color option of the dashboard is not appealing to them and would like to have different color options that would make readability easier.

5.5. Summary

Considering the population growth, urbanization levels, and waste generation trends within Tshwane, revealing an approximate waste production of 6,902.44 Tons/day from residential, commercial, and industrial sources. Within the study area the production is estimated in 456.51 Tons/day. The waste collection scheme involves weekly collection by the municipality, with daily collection for restaurants and provisions for private waste collection by individual businesses. Foot workers engaged in litter collection operate in an "as the need arises" approach, with specific schedules for different tasks.

Stakeholders are categorized into power, urgency, legitimacy, and proximity typologies. Due to its regulatory influence, the Municipality emerges as a Definitive stakeholder. The City Improvement District (CID) and the Ward Councilor, who are directly responsible for local community governance and service delivery, are classified as Crucial Stakeholders. These three stakeholders are considered the final users of the Digital Twin Prototype.

A total of 32 stakeholder requirements for solid waste management improvement are identified, encompassing strategic, performance, and operational aspects. These requirements emphasize goals such as carbon footprint reduction, alignment with Sustainable Development Goals (SDGs), and efficient waste collection routes. The study also highlights the challenges in incorporating all identified requirements within the Waste Digital Twin prototype due to resource constraints and external data availability.

The data collection phase of the study focused on solid waste containers and littering identification within the study area. A total of 2.236 reports were collected, out of which 3.04% were invalid and 3.76% were inaccurate. A total of 1,270 solid waste containers were identified in 1,151 locations, with 4.16% reported as broken. Additionally, 136 ashtrays were identified within the campus area. The study identified various types of containers, with 118L and 240L containers being the most frequent. The data revealed that public spaces had an uneven distribution of waste containers, and some areas lacked waste container records.

The urban waste management digital twin was designed based on building identification, waste generation, and collection optimization. A total of 4,768 buildings were identified, with their attributes updated for 3D reconstruction. The buildings were assigned to the closest waste container, and waste generation simulations were conducted. The optimal collection routes were calculated considering various factors such as road networks, unidirectional segments, and waste production. A dashboard was designed to visualize key indicators, including container saturation, waste generation, and optimal collection routes. Performance assessments showed differences in simulation speed between local and cloud services.

Stakeholder assessments indicated that the dashboard was generally well-received, with users finding it useful for collaboration and addressing waste management challenges. However, there were suggestions for improving the communicative value of the dashboard, especially in conveying waste quantities and container saturation. The need for clear communication of the tool's purpose and goals to stakeholders was highlighted. Municipal officials emphasized the need to demonstrate the tool's value beyond being a GIS tool. Hatfield CID stakeholders found value in visualizing their impact on waste management, while industrial park stakeholders pointed out limitations related to restricted areas. Residents appreciated the data accessibility but suggested improvements in the dashboard's color scheme and incentives for citizen engagement in reporting.

6. DISCUSSION

The discussion is organized into four segments to address various aspects of the research, starting with the analysis of the prototype under the Gemini Priniciples, its benefits and practical implications of the design, followed by considerations related to security, data accuracy, scalability, stakeholder engagement, and challenges encountered during the research process. The section highlights the significance of urban digital twins in waste management and their potential to drive more sustainable and cost-effective practices.

6.1. Gemini Principles analysis

6.1.1. Purpose

The design of this digital twin allows for focusing efforts on bins nearing capacity, reducing unnecessary collections and saving time. By identifying littering locations through the digital twin, authorities can take targeted actions to address littering hotspots. This can involve increasing the number of bins in heavily littered areas or implementing located awareness campaigns to promote responsible waste disposal. By optimizing collection routes and schedules, this digital twin can lead to a more efficient and timely waste pickup. Reducing unnecessary trips minimizes fuel consumption, labor, vehicle maintenance, and greenhouse gas emissions. Proper waste management helps maintain a clean and hygienic environment, reducing the risk of diseases associated with waste accumulation. It supports the United Nations' Sustainable Development Goals, including Goal 11 (Sustainable Cities and Communities) and Goal 12 (Responsible Consumption and Production). Also, it contributes to aesthetically pleasing surroundings, enhancing residents' and visitors' overall quality of life.

The digital twin generates valuable data on waste generation patterns, bin usage, and littering locations. Analyzing this data can lead to data-driven decision-making and evidence-based policies for further improving waste management practices. Residents can actively participate in keeping their neighborhoods clean and environmentally friendly by providing information about waste disposal and collection, creating *waste governance*. On this approach, residents can inform the local authorities of broken containers that need to be replaced, reducing downtime and avoiding littering due to a lack of suitable state containers.

Although the purpose of digital twinning waste management is evident for this researcher, it is necessary to include better communication practices to allow stakeholders to understand this approach's capabilities and potential uses. During the stakeholders' workshop, it was manifested that the purposefulness is unclear for the definite stakeholders.

6.1.2. Trust

The current setup of the architecture includes a low level of security with only access control as a measure. The process will need to evolve to include vulnerability assessments, secure API connection, and authentication for data managers. It is necessary to include backup and disaster recovery protocols so information is not lost in case of unforeseen events.

Although the data collection is designed to be open to everyone and does not collect personal information, data accuracy procedures must be integrated to ensure high quality. Epicollect5 presents a challenge in guaranteeing that collected photographs do not have explicit or inappropriate content that can be offensive or harmful to others. Therefore, implementing an efficient and robust content moderation system is imperative to identify and prevent disseminating these types of images. Developing sophisticated algorithms and human oversight mechanisms to detect and remove such content promptly will uphold the digital twin integrity and ensure a positive user experience for all participants.

Moving the waste generation, route optimization calculations, and dashboard control to completely open-source components will also be necessary to enforce the openness of the digital twin. This would imply migrating the tool to a server that allows for open libraries integration and covers the associated cost of deploying and maintaining the platform. This process would require in-depth knowledge of Python libraries and programming skills that allow the integration of different APIs and other methods for route optimization, such as the ones designed by Coupey et al. (2023) and Montagné et al. (2020).

Data accuracy regarding the number of people residing in each building is limited by the method used by Schiavina et al. (2022). This has created some imbalances, such as single houses with 16 inhabitants, which could be unrealistic. To improve the accuracy is possible to integrate census data, such as the unpublished results of Census 2022 from the Department of Statistics South Africa.

6.1.3. Function

The designed architecture's effective function depends on waste simulations as it does not require additional investments. To move this design to other scenarios with larger financial capacity, it is possible to integrate sensors to monitor container fill levels, GPS trackers for collection vehicles, and cameras for littering detection. Combining these technologies would require connection via LoRaWAN protocols and networks that can transmit data asynchronously, allowing real-time waste monitoring.

Implementing the waste digital twin requires establishing ownership from the municipality, as managing stakeholders, and governance from all the different actors identified on phase I of this research. Additionally, it is required to establish regulations and guidelines for security, access control, data protection, and privacy.

The designed architecture enables scalability to increase the number of containers, volume capacity and waste generation. It also allows for an extension of the road network to cover a larger operational area and adaptability on the number and type of collection vehicles. It is necessary to encourage larger user feedback and active stakeholder engagement to adapt to changing user needs and requirements as the system implementation evolves. By embracing adaptability, the digital twin can evolve alongside technological advancements and societal changes, making it a valuable and sustainable tool for long-term waste management solutions.

6.2. Findings

Identifying and classifying the stakeholders in developing digital twins sometimes is overlooked by other researches (Bartos & Kerkez, 2021; Jiang et al., 2022; Xu et al., 2022; Yu et al., 2023). By analyzing stakeholders on the four different attributes, it was possible to determine the main stakeholders that become users of the tool are the City Improvement District, the Ward representative, and the Municipality waste department. The type of stakeholders that become final users of the tool possesses a common characteristic: their political power and the current dynamics between them and other stakeholders.

Using the Salience model combined with a pairwise comparison, the subjectivity of the classification into the different typologies that Mitchell et al. (1997) and Shafique & Gabriel (2022) include in their classification method can be reduced. It does not eliminate it, as the pairwise comparison also requires a degree of subjectivity when analyzing and comparing each stakeholder in their categories. Using this method also helps to determine the importance of each stakeholder, focusing on each specific case and location. In this particular case, the Ward Councilor is essential as he is the key to communication between residents and other actors. Such a situation can be untrue in other parts of the country that does not possess such a strong political structure. Smaller cities and rural areas can have different dynamics where social leaders and direct contact from residents to municipalities can take a higher role.

Data collection provided insights into the uneven distribution of solid waste containers within the study area. Certain areas might be overburdened with waste, leading to overflow and environmental hazards, while other regions may lack sufficient waste containers, resulting in littering and illegal dumping. The data showed the Hatfield CID on littering cleaning and a more significant concentration of containers around educational areas. These patterns and locations inform where interventions should be made, e.g., larger containers close to the stadium and Hatfield Plaza, higher collection frequency along the M7 route, traffic restrictions, or road maintenance on roads frequently transited by collection trucks. Likewise, it is possible to determine the areas in which high frequency is not required, mainly in exclusive residential areas, and explore the possibility of requesting residents to deposit their waste in a more centralized container rather than doing so on their own in their front yard.

Waste generation simulations allow an understanding of the waste flows from buildings to containers and identify areas with large production and small capacity that need to be intervened. As the assignment of buildings to containers does not consider access restriction, the actual container where a citizen would drop their waste to be collected is inaccurate. However, it provides a proxy of the collection places and can give insights of larger container placement that can reduce the loading time trucks currently perform as they go home by home. By clustering, this time can be reduced, and the man-working hours can also be diminished. Therefore, overall operation cost is decreased. Nonetheless, it is also necessary to make the waste flow analysis in a Manhattan distance movement, not a Euclidean one, as people can not move in an "as the crow flies" way inside a city.

The proposed container aggregation method is far more straightforward than those explored by other authors like Al-Refaie et al., (2020) and Viktorin et al., (2023b)as it has fewer elements to analyze. As the problem becomes bigger, with more buildings and containers to assign, the overall performance can be reduced. Nonetheless, as only the number of inputs will affect the performance, the method allows for rapid adaptation with more extensive data collection and change of volumes as the city adapts to such kind of technology and citizens make new reports.

The current collection scheme, where one vehicle is assigned to the area for waste collection and does it weekly, seems insufficient for the large waste production. However, as there are multiple waste collection companies operating with businesses and large producers, it is necessary to map all collection actors, the daily generated quantities, and the rate of waste segregation at source to be able to have a complete picture of waste flows and recalculate the requirements for optimal collection routes.

The proposed optimization for waste collection approximates the solution of multiple nodes to be collected, reducing operational times, fuel composition, and the consequent reduction of greenhouse gas emissions. The cost of the optimized collection routes would be 1,932,554 ZAR (101,623 USD) per year only in the study area, which represents 0.11% of the overall city Waste Management budget (2023-2024 Medium-Term Revenue and Expenditure Framework for the City of Tshwane, 2023), an important amount considering that the study area covers 0.15% of the city, and this cost is related to only fuel consumption. Additional costs are associated with waste management, such as landfill operation, workers' wages, container and trash bags provision and vehicle maintenance, which also need to be considered. Although this scenario corresponds to an improved waste collection routing, currently, it is impossible to estimate the improvement rate as there is no data on vehicles' current paths, total fuel consumption, waste dumped in landfills and detailed collection and transport expenditure. Nonetheless, this cost estimation indicates that the total budget needs to be expanded so the city can cover all the solid waste management costs.

Due to the low number of responses, it is impossible to prove that an operation control dashboard is the correct method for integrating the information and making it accessible to the stakeholders in the solid waste management twinning workflow. Even though stakeholders provided high scores in user-friendliness, interactivity, spatial interface, interactivity, consensus, effectiveness, and communicative value indicators, more respondents would be required to make such conclusions.

6.3. Limitations

The research faced some adversities as the proposed data collection method did not consider regional numerical format. Some of the collecting devices (iOS) could not include decimal separators, and data was informed in the comments section of the report. This generates anomalies in the monitoring as geometrical properties and volume capacity could not be visualized on the spot, and digitation mistakes could have been made in the data collection.

It is possible that, during data collection, some hidden containers were not identifiable. Due to security concerns, it is common practice for residents of Tshwane to move their containers to non-visible places so they can not be stolen. This creates an incomplete mapping of all the waste containers available and the consequential changes in container aggregation and capacity availability.

The waste calculations and categorization of non-residential buildings were performed using data from 2008 in Athens, Greece, a non-African country with more than double the GDP per capita of South Africa (World Bank, 2022). The difference in time (15 years ago), consumption patterns, type of business, and waste segregation can significantly affect the amount of waste generated at each building. Therefore, the calculations on waste generation are not accurate in the Tshwane context.

The data of generated waste could not be compared to the real scenario as there is no existing data on the volume dumped in landfill. Landfill operators do not register the volume being dumped, and the place operates more as an open-access dumpster than a properly regulated landfill. The data integration and availability of the dashboard online were limited to the resources available for the research. A complete open-source digital twin, with access to anyone through HTTP protocols, would require acquiring a virtual machine on a cloud server and installing different packages and libraries. Financial costs associated with deployment, operation and maintenance were not available for this research. Additionally, for a waste management digital twin to operate on open source platforms, it is required a multidisciplinary team with knowledge of environmental management, finances, computer science, in-depth programming skills, and of course, geographical information systems.

6.4. Implications

Urban digital twins offer a solution by providing real-time data on the locations and capacities of existing containers. By visualizing this data, waste management authorities can identify areas with inadequate coverage and strategize container placement for improved waste collection.

By involving citizen participation, the proposed method reduces challenges, such as location accuracy, high resource requirements, and disagreement on labeling, identified in Artificial Intelligence computer vision detection research (Moral et al., 2022). It also confirms the importance of citizen testimony in mapping solid waste (Al-Joburi, 2018). The real-time monitoring helps address the randomness of low-severity littering for improved solid waste management, including multiple stakeholders.

The design of this digital Twin allows for multiple collaborations between stakeholders and improves the communication and transparency of the process. It enforces the arguments of Hämäläinen (2021) on the benefit the digital twins can provide for decision-making where heterogeneous stakeholders are at the table. The link between urban developers and citizens can be shortened and strengthened by applying these technologies, giving the residents the possibility of governance in their solid waste.

The digital twin design allows for different tests and calculations where the current volume capacity of the identified containers allows to detect areas where overflow can occur. Modifying the values makes it possible to calculate the capacity required for a specific location and simulate the effects on the collection.

Waste collection often accounts for a significant portion of a city's budget. By implementing a digital twinning approach to waste management systems, authorities can access real-time information on waste container fill levels and plan optimized collection routes. This can reduce fuel consumption, lower vehicle emissions, and minimize operational expenses, resulting in a more sustainable and cost-effective waste management process.

Crucial and Definitive stakeholders can gain insights into the system's dynamics by visually representing the city's waste management infrastructure, including containers, littering, collection vehicles, and disposal facilities. This allows them to simulate different scenarios and optimize collection strategies based on various factors, such as waste generation patterns, changes in population, and traffic restrictions.

Digital Twinning can also be the basis of a decision support system for more strategic waste management initiatives. When considering the need for new waste containers or the modification of existing ones, digital twins can be employed to simulate and assess the impact of these changes on waste collection efficiency and overall cost-effectiveness. Additionally, urban digital twins enable better adaptation to changing waste disposal requirements by providing a dynamic model that can be continuously updated with real-world data.

6.5. Summary

The primary purpose of this digital twin is to enhance waste management by optimizing waste collection routes, identifying littering hotspots, and promoting sustainable waste disposal. The system's benefits encompass efficient waste pickup, reduced fuel consumption, improved environmental conditions, and alignment with Sustainable Development Goals. The ability to simulate scenarios and adapt to changing requirements is a key benefit, with the digital twin serving as a dynamic decision support system that can have an impact on cost reduction and strategic waste initiatives.

Enhanced security measures, data accuracy, and content moderation are needed to increase the trust of the developed twin. The architecture's transition to open-source components, LoRaWAN integration, and robust data protection mechanisms are considered necessary. Moreover, incorporating accurate census data and open-source route optimization methods is suggested to reinforce the system's integrity.

The system's effectiveness depends on waste simulations, the input data quality, and potential enhancements including sensor integration for real-time monitoring. Stakeholder engagement, governance establishment, and regulatory frameworks are required for successful implementation. The prototyped Waste digital twin architecture enables expansion, adaptability, and long-term viability.

Using the Salience model combined with pairwise comparison aids in stakeholder assessment and importance determination while diminishing, yet not eliminating, analysis subjectivity. Data insights reveal patterns in waste generation distribution and allocation while suggesting targeted interventions in areas with low waste capacity and high generation. Waste generation simulations and optimization strategies are proposed, while acknowledging data limitations and the need for more extensive feedback on the perceived quality of the Waste digital twin.

Some limitations were faced during research, including data collection anomalies, hidden containers, and accuracy issues in waste calculations. It is important to improve data quality and work with a multidisciplinary expertise group and assign financial resources for effective digital twin deployment, Citizen engagement, and stakeholders' collaboration.

7. FUTURE WORK

Future development of a Waste Management digital twin will require integrating the waste separation at the source and the type of waste generated at each building. Mapping these flows can help reduce the material consumption footprint and enhance circular economies on biowaste, construction materials, and packaging. It is also necessary to include waste pickers as key members of the waste management scheme and their vital role in waste reduction.

Different sensors can measure container capacity in the city. This will imply an additional cost for sensor installments and communication of data changes. Identification of littering and illegal dumping sites can be enhanced with frontal and lateral cameras on waste collection vehicles that, through image segmentation, can detect the location and volumes of waste that need cleaning from streets. Further research could explore the effectiveness of interventions informed by this data, such as targeted container placement or increased cleaning frequency in areas with high littering.

The proposed method in this research can also be applied to other areas that require operational planning, such as fire, flood, health and security emergency response. Where citizens can make reports via Epicollect, data collection and aggregation can be performed. Later, vehicle route optimization can deliver faster responses to events while reducing operation costs and having a control system that records previous events. Digital Twinning emergency response can allow to make simulations of multi-incident events and provide preparation and cost estimation for the response teams.

8. CONCLUSIONS

Current solid waste management methods in Tshwane include zoning and the number of homes per land unit as geospatial information for collection operation. The municipality's collection scheme encompasses regular waste pickups for residences and businesses, with specific arrangements for high-waste producers like restaurants. Private waste collection services are also available for individual businesses, offering additional flexibility. The city employs a team of foot workers to address littering in public areas, and while they lack a fixed schedule, they adopt an on-demand approach. Despite the commendable efforts by the City Improvement District (CID) to improve street cleanliness with a dedicated team and truck, a comprehensive and connected waste strategy for the entire precinct is inexistent. Challenges persist regarding waste segregation and the open accessibility of dumping sites to the public, necessitating further focus on sustainable waste management strategies for the city's environmental well-being, such as Digital Twinning.

Twelve stakeholders were involved in the solid waste management scheme who were considered for developing the Waste management digital twin. When employing the Salience Model to organize stakeholders, the CID and Ward Councilor emerged as crucial stakeholders, ranking high in all four attributes. The municipality was classified as a Definitive Stakeholder, boasting high scores in three attributes but slightly lower proximity than others. As a result of this classification, these three stakeholders were identified as primary end-users of the proposed Digital Twin tool for waste management.

The stakeholder analysis for improving solid waste management through the development of a Waste Management Digital Twin identified a comprehensive list of 32 user requirements across three categories: Strategic, Performance, and Operational. The final requirements integrated into the digital twin encompass crucial aspects such as identifying polluters, scalability to the country level, tracking SDG goal performance, monitoring waste generation, optimizing container locations, measuring fuel consumption of trucks, and generating waste production heatmaps. Furthermore, the Digital Twin incorporates operational features like container capacity level, real-time waste production monitoring, and a visually simple design, ensuring accessibility to illiterate users. By focusing on these selected requirements, the Waste Management Digital Twin aims to address the diverse needs of stakeholders and contribute to a more efficient and sustainable waste management system at the city level.

Developing a Waste Management Digital Twin required integrating container location, volume and status characteristics, location of littering, building characterization, population data, road network, transit restrictions, and destination location as geospatial elements. Additionally, collection vehicle capacities and dumping conditions were necessary as non-spatial data that allows for collection route optimization. Integrating such elements required data aggregation, online storage on a server, route optimization through Python using the Tabu search metaheuristic method and creating a web app dashboard for data display and interactivity.

The results indicated that simulating on a local setup yielded faster processing times, and moving to a cloud service led to significant increases in processing durations for waste generation calculation and optimal collection route determination. These delays were attributed to the structure of the process, where online stored layers required record downloads and individual updates rather than updating all tuples at once. Furthermore, the stakeholders' assessment of the dashboard demonstrated a generally positive reception, with high scores obtained in various categories. However, concerns were raised regarding data accuracy, decision-making support, and the need to improve the communicative value of the dashboard. The stakeholder survey's response rate limited some results' reliability, but open discussions with stakeholders provided valuable insights into the tool's potential applications and areas for improvement. Addressing issues related to tool objectives, explaining its purpose to stakeholders, and enhancing data accessibility and user-friendliness are crucial aspects to consider in further developing urban digital twins for optimized solid waste management. Additionally, efforts to incorporate restricted areas and incentives for citizen engagement in data reporting can contribute to the tool's effectiveness and broader adoption within waste management processes.

Digital twinning, multi-stakeholder engagement, and citizen participation could provide valuable insights into the distribution of solid waste containers and the occurrence of illegal dumping and littering. It can be a hybrid and collective approach for addressing solid waste management challenges in lower-income countries without large financial and technological capacity. The digital twin can provide transparent data on waste management operations and performance. This transparency fosters public trust and allows stakeholders to track progress toward waste management goals and environmental targets, items identified as critical requirements from stakeholders' points of view.

Citizen participation, facilitated by the digital twinning technology, reports littering incidents and maps waste container locations. Enforced by digital twins, route optimization reduces costs and enhances collection efficiency. Moreover, digital twins serve as invaluable decision support systems, aiding operational planning and allocating new containers to adapt to evolving waste disposal needs. Integrating urban digital twins in solid waste management represents a transformative step towards sustainable and cost-effective waste management practices, promising cleaner and environmentally friendly urban environments.

By developing digital counterparts of waste management infrastructure and mapping out their spatial distribution, policymakers and stakeholders comprehensively understand the current state of solid waste container placement. This knowledge serves as a decision-making support system for targeted interventions. Through collective efforts and integration of technology and community engagement, improved solid waste management can be achieved, even in resource-constrained settings.

9. ETHICAL CONSIDERATIONS

The research was conducted for academic purposes; no external sponsors are particularly interested in the results. A local university with on-site knowledge of the city dynamics supported the overall process to ease communication with stakeholders and understand the population's local dynamics. It is essential to highlight that the University of Pretoria was particularly interested in this research as it relates to the academic work that the Faculty of Engineering, Built Environment, and Information Technology are performing.

Geospatial data collected during the process is safeguarded in the University of Twente cloud storage. The University approved the designed workshop and questionnaires of Twente's ethics committee. Workshops and questionnaires were performed online and recorded; they did not include information related to a household or personal level. All transcripts were anonymized to avoid possible conflicts between stakeholders. Consent was taken from the sources before conducting the workshops. The participants have the right to withdraw their consent and get their data back if they want in the future. All sensitive information was deleted after the research was concluded. Reports of illegal dumping site locations were discussed only with local authorities to avoid *bullying* or shaming of neighbors.

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11. ANNEXES

11.1. Epicollect5 Guide

HATFIELD WASTE

THE ULTIMATE GUIDE TO EPICOLLECT5 SURVEY

Say hello to clean communities! This guide will take you through the process of using EpiCollect5 to collect trash bin and littering locations.

With this powerful tool, you'll be able to gather information about these issues in your area and help put an end to illegal dumping.

Whether you're new to EpiCollect5 or a seasoned user, this guide will provide you with all the knowledge you need to get started.

So, let's dive in and make a difference together!

HATFIELD WASTE

Your task!

1. - Divide in teams of 3 people. And select a leader.
   - Find your grid zone on the map provided (click here), zoom in to see the name.

2. - Each team will select 10 zones of the grid to work with. Make sure two teams don't have the same zones

3. Walk the streets from your grid and identify all the trash bins that you see. Make a record on Epicollect5. Do not tresppass!

4. If you see trash on the street also mark them on the app as littering report.

5. If you are done with your zone, contact other team leader and help them.

HATFIELD WASTE

epicollect5

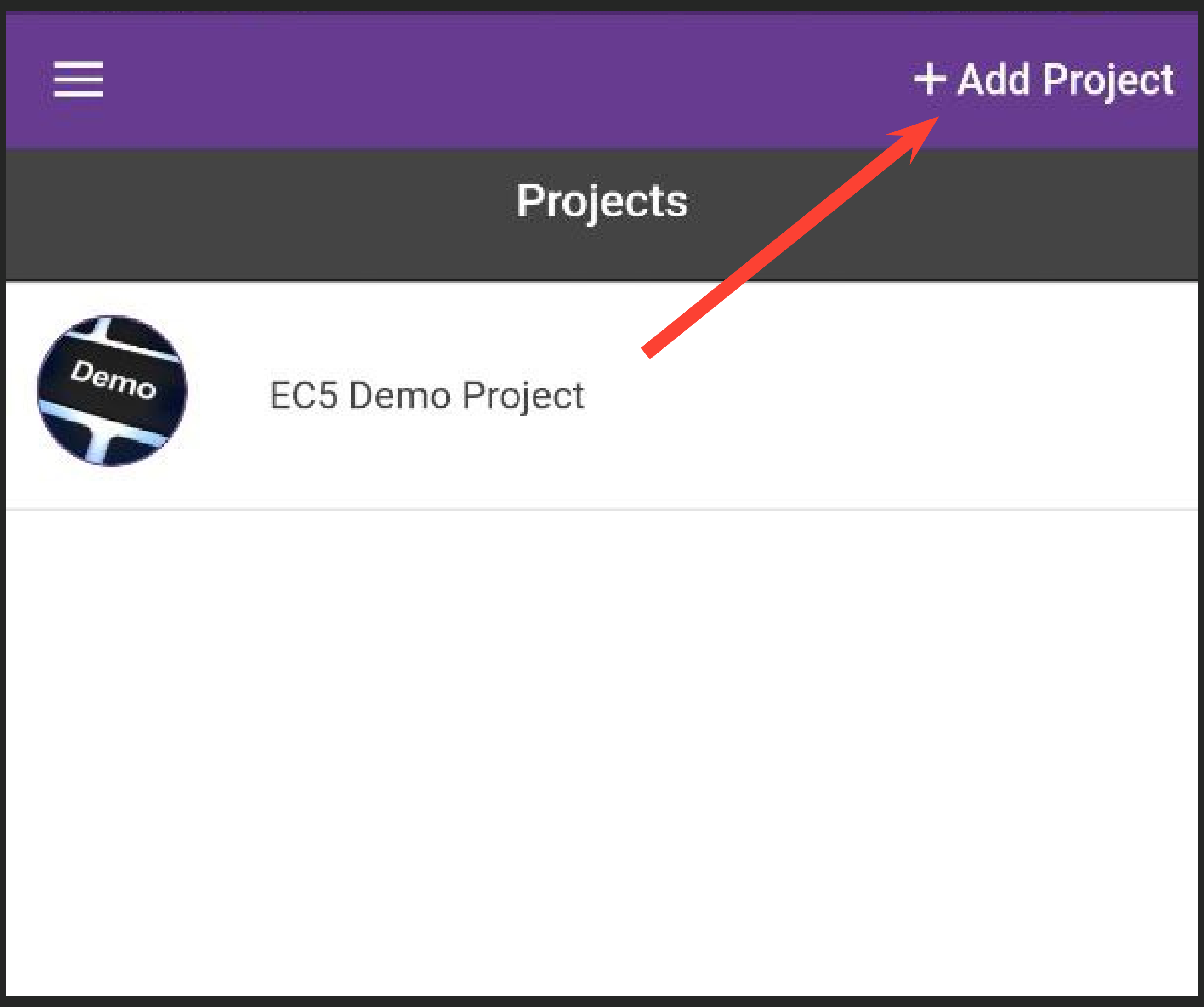
Guide

1. Download the epiCollect5 app for Android or iOS

GET IT ON Google Play

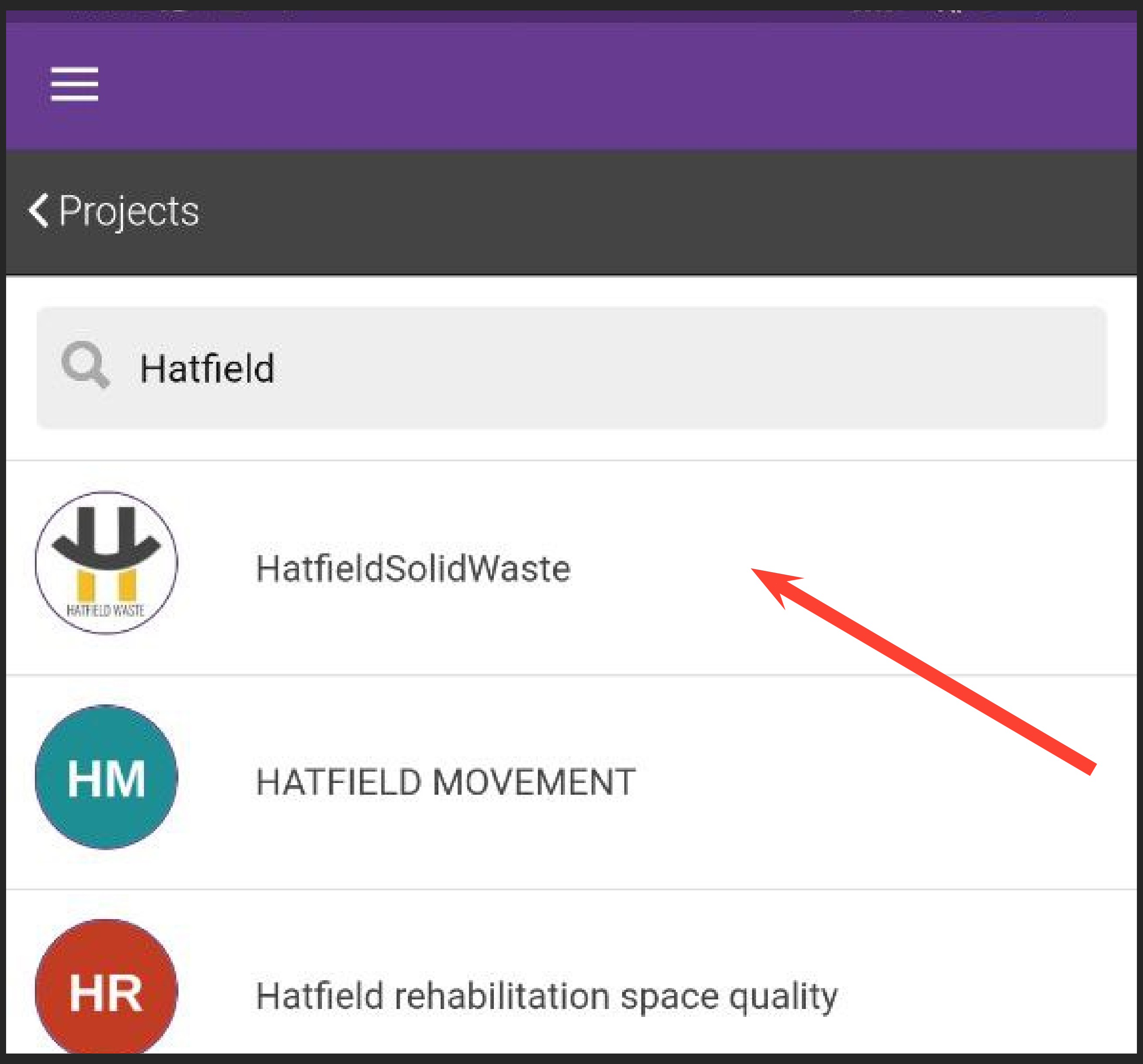
Available on the App Store

2.



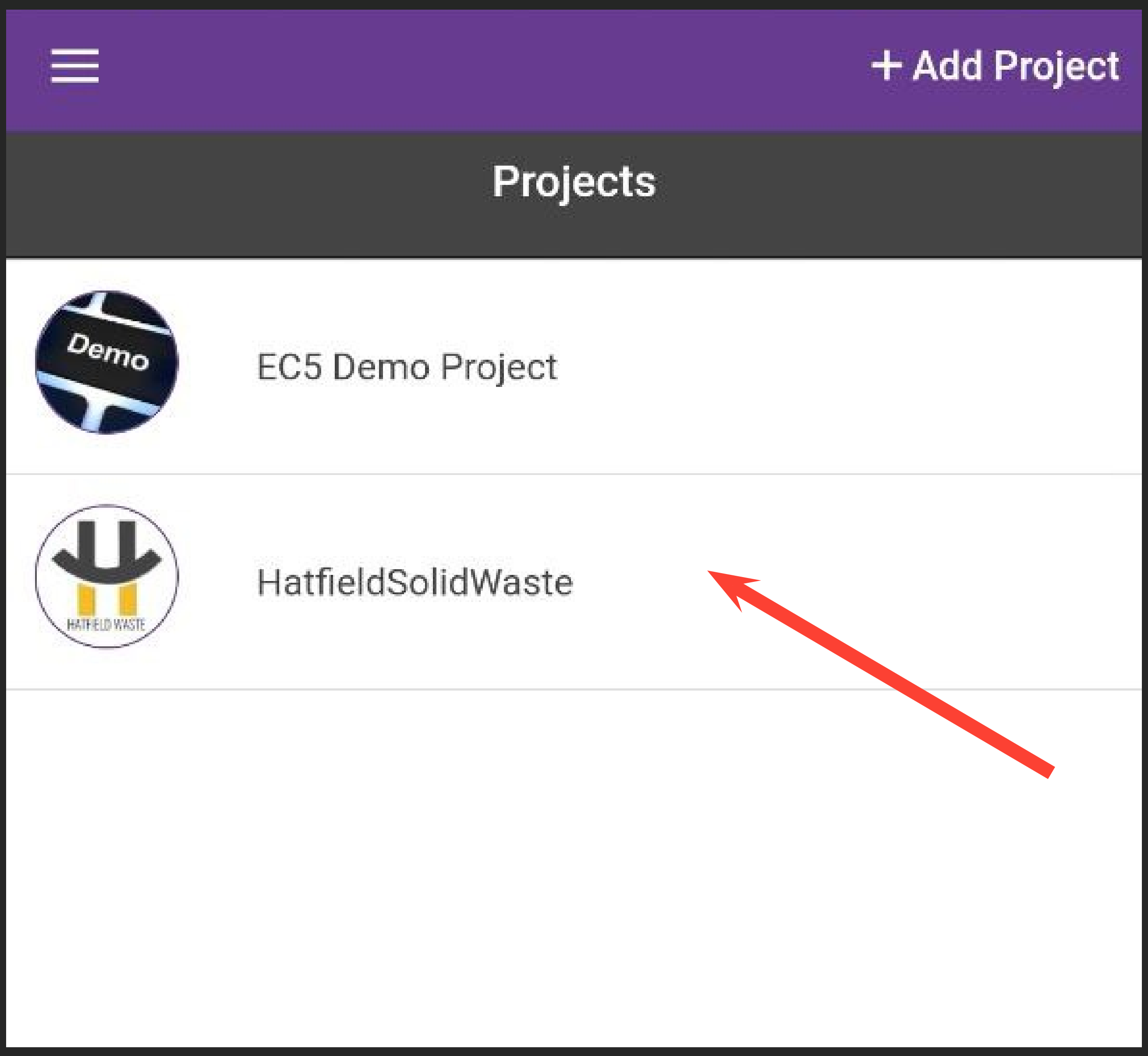
Tap on **Add Project**

3.



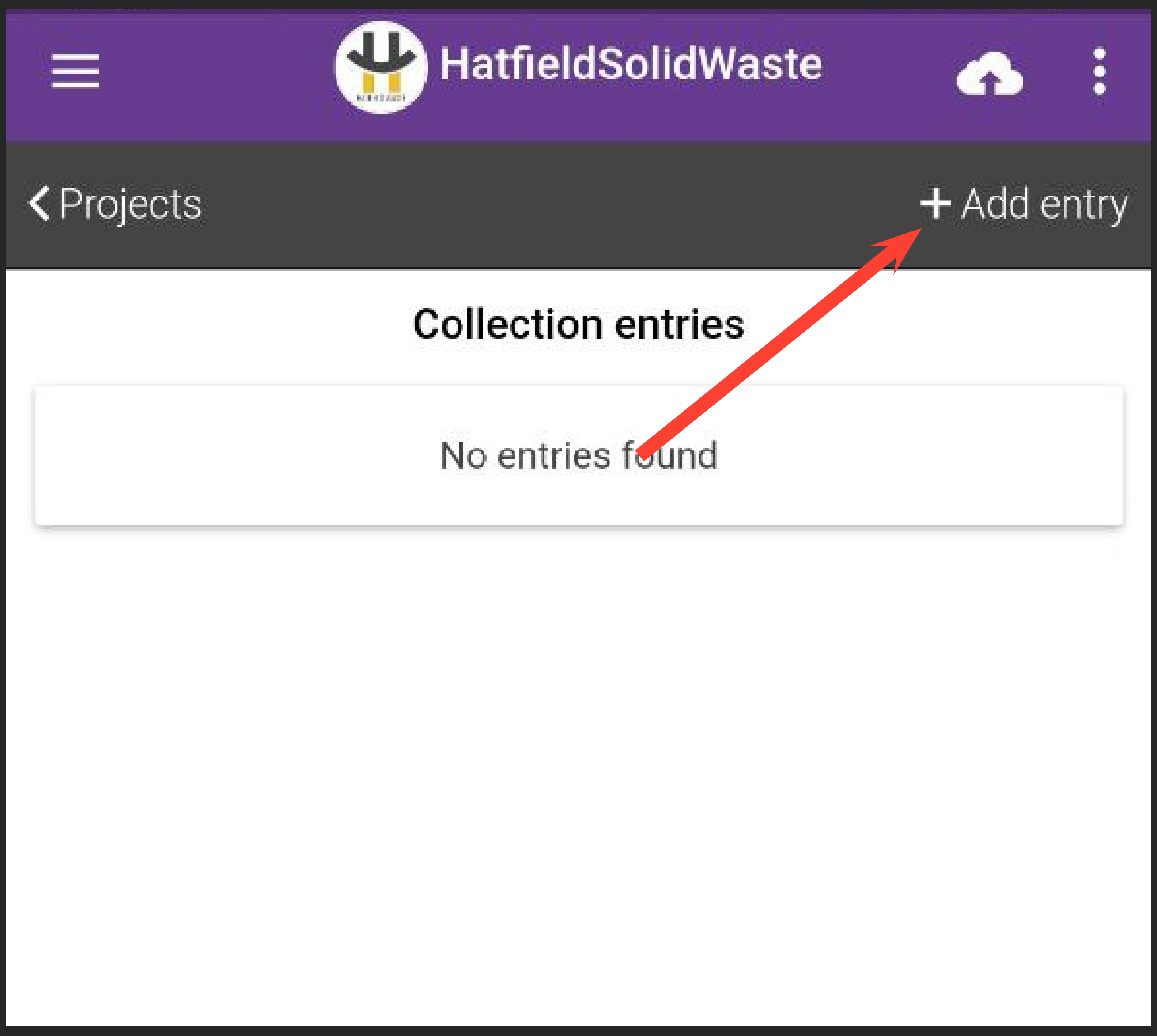
Search for Hatfield Solid Waste and **tap on the result**

4.



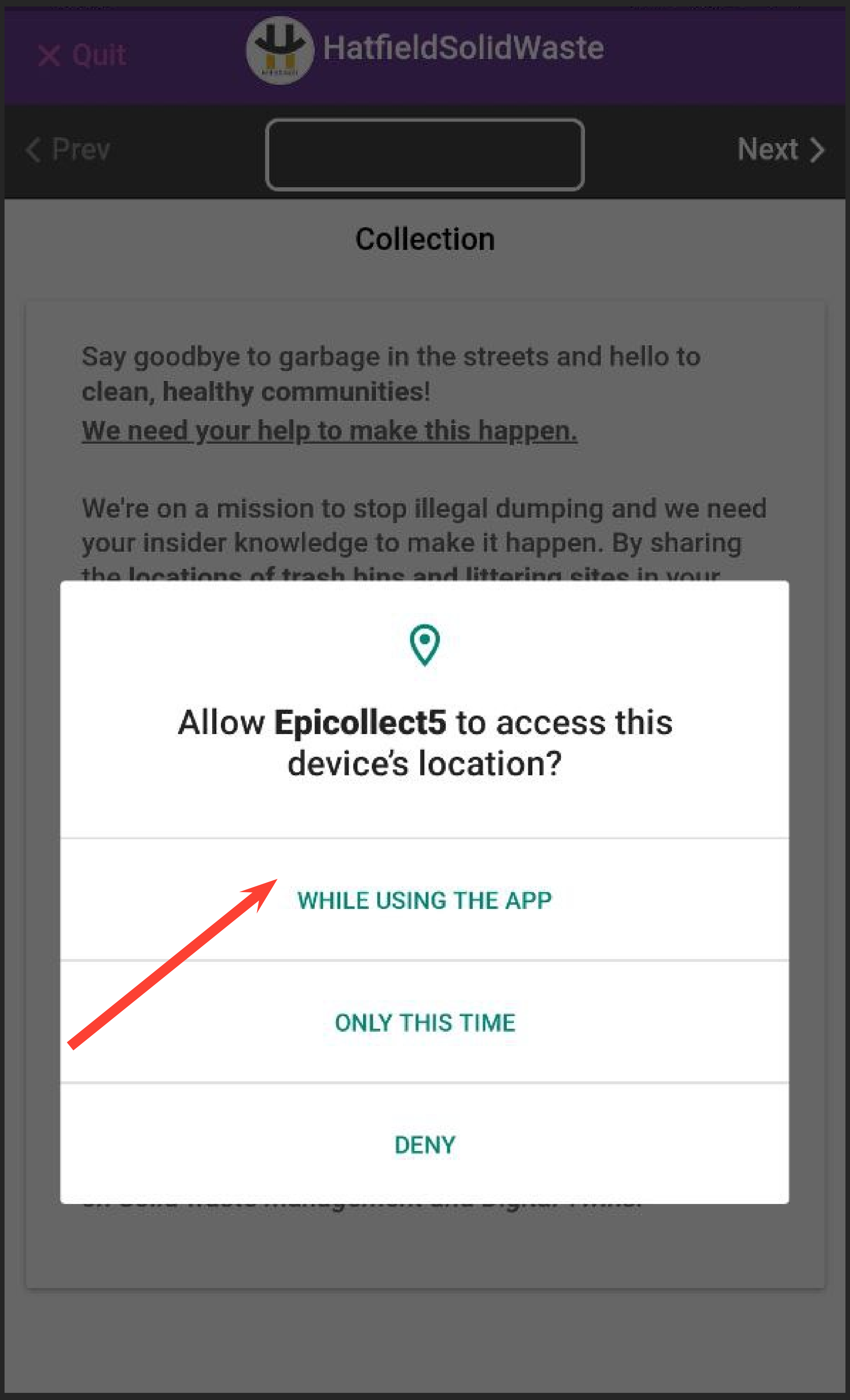
The survey will now appear in your projects. Tap the project to open it

5.



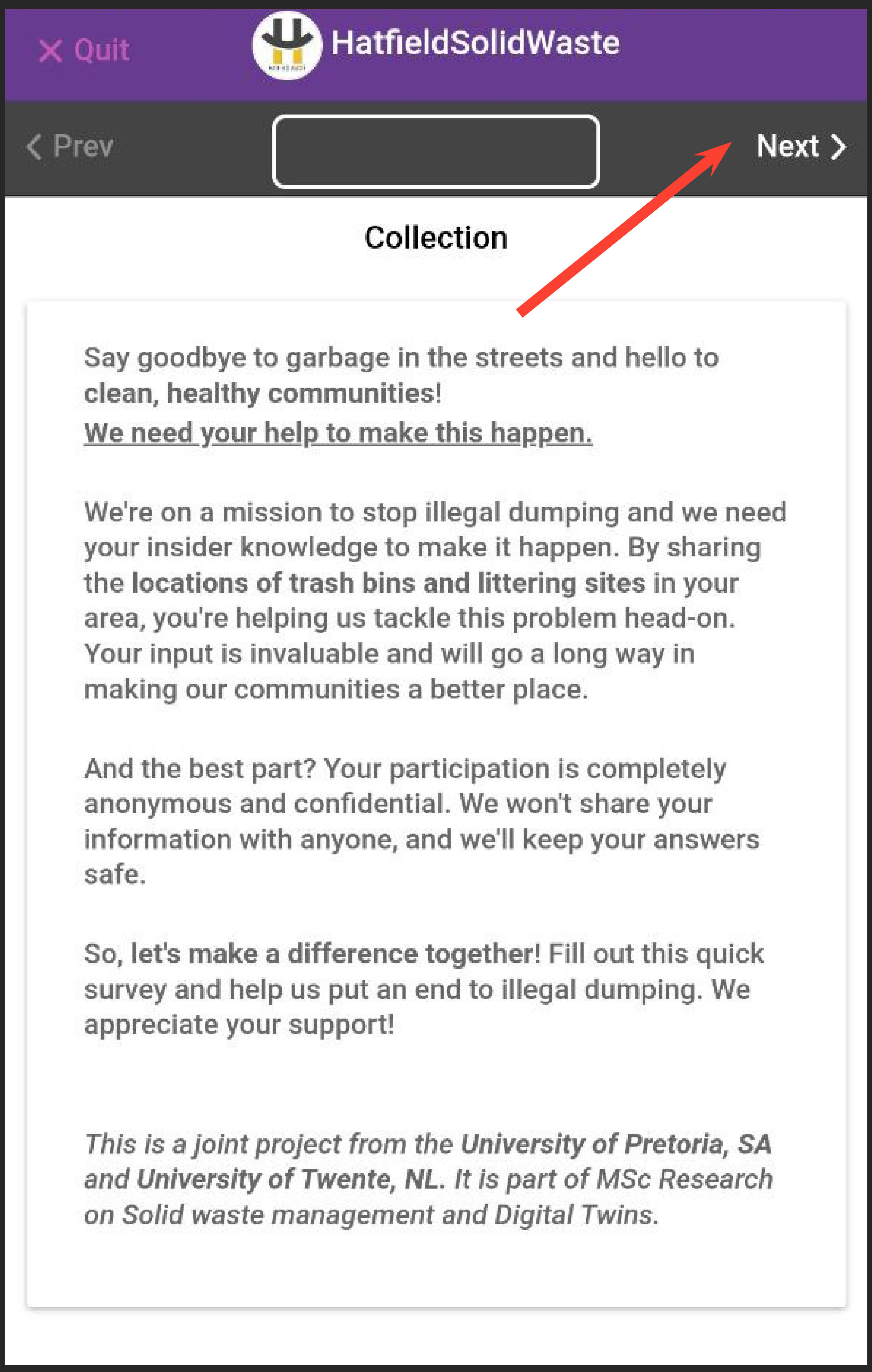
Now tap on Add entry to start the survey

6.



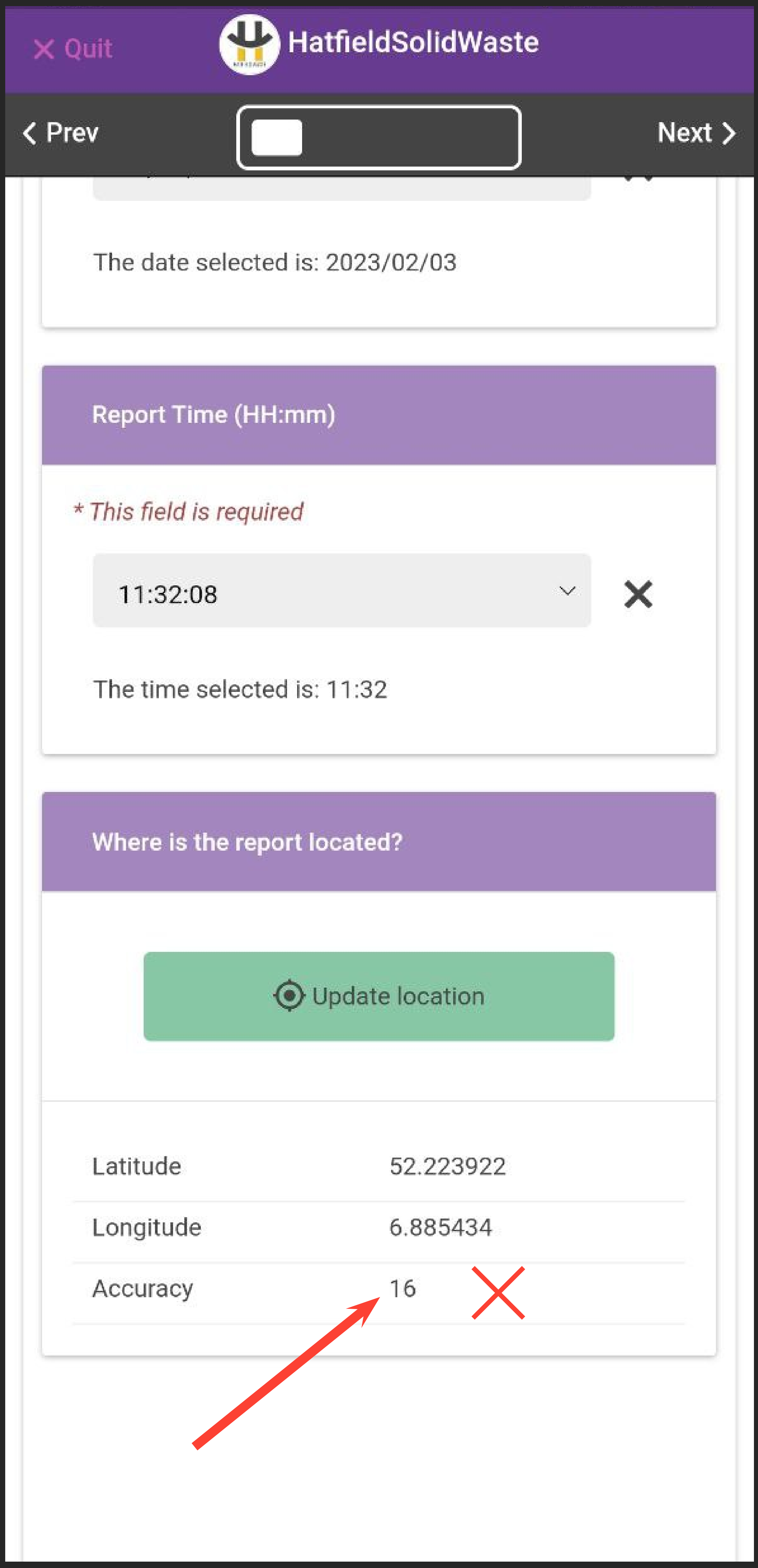
Grant the location permit to the app.

7.



Read the Welcome page, when you are ready tap on Next to start collecting information

8.

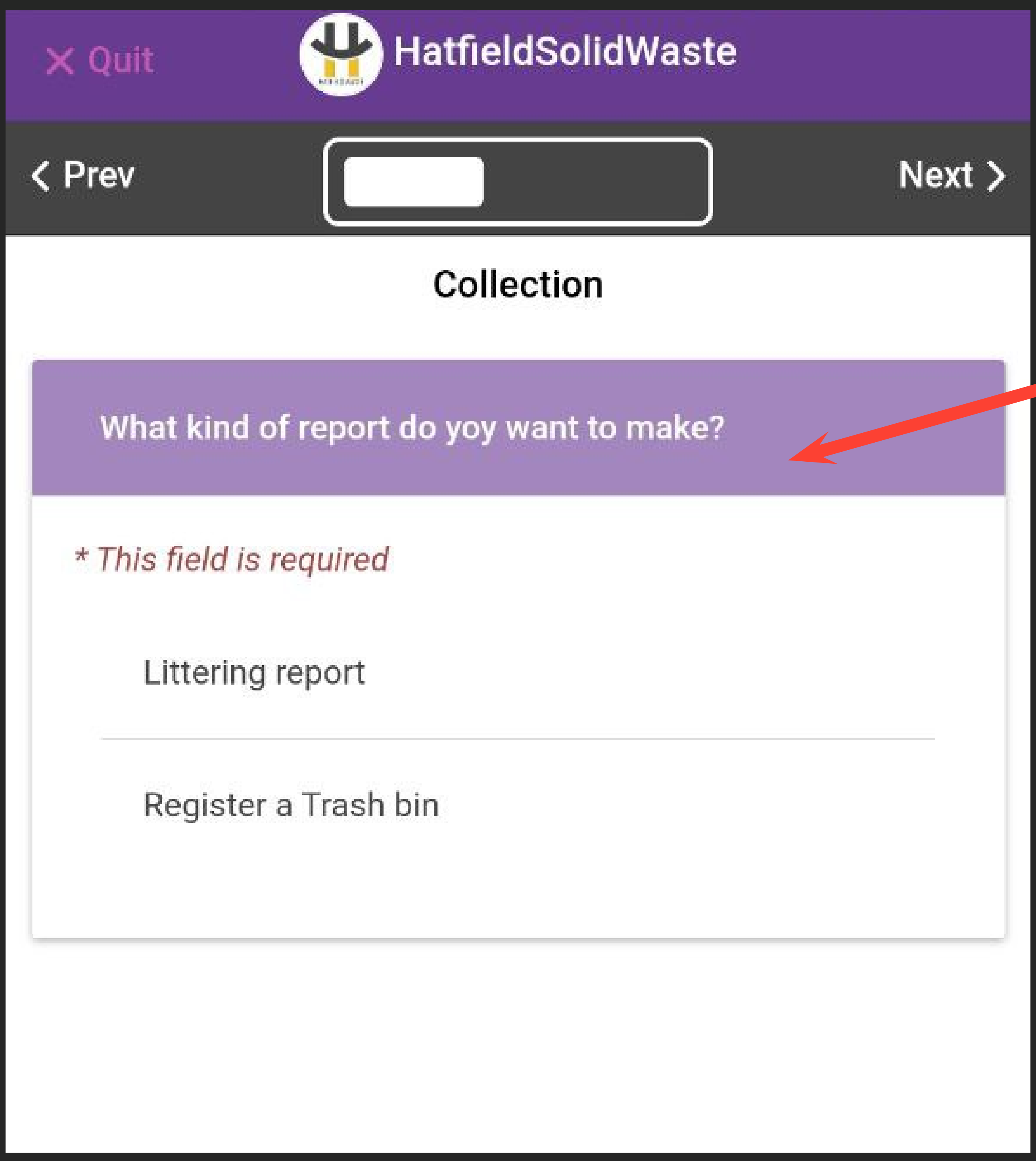


On the second page you will be asked about the time and date of the report. By default it will load the current date and time.

Tap update location to calculate your coordinates. Make sure your accuracy is **5 or lower.**

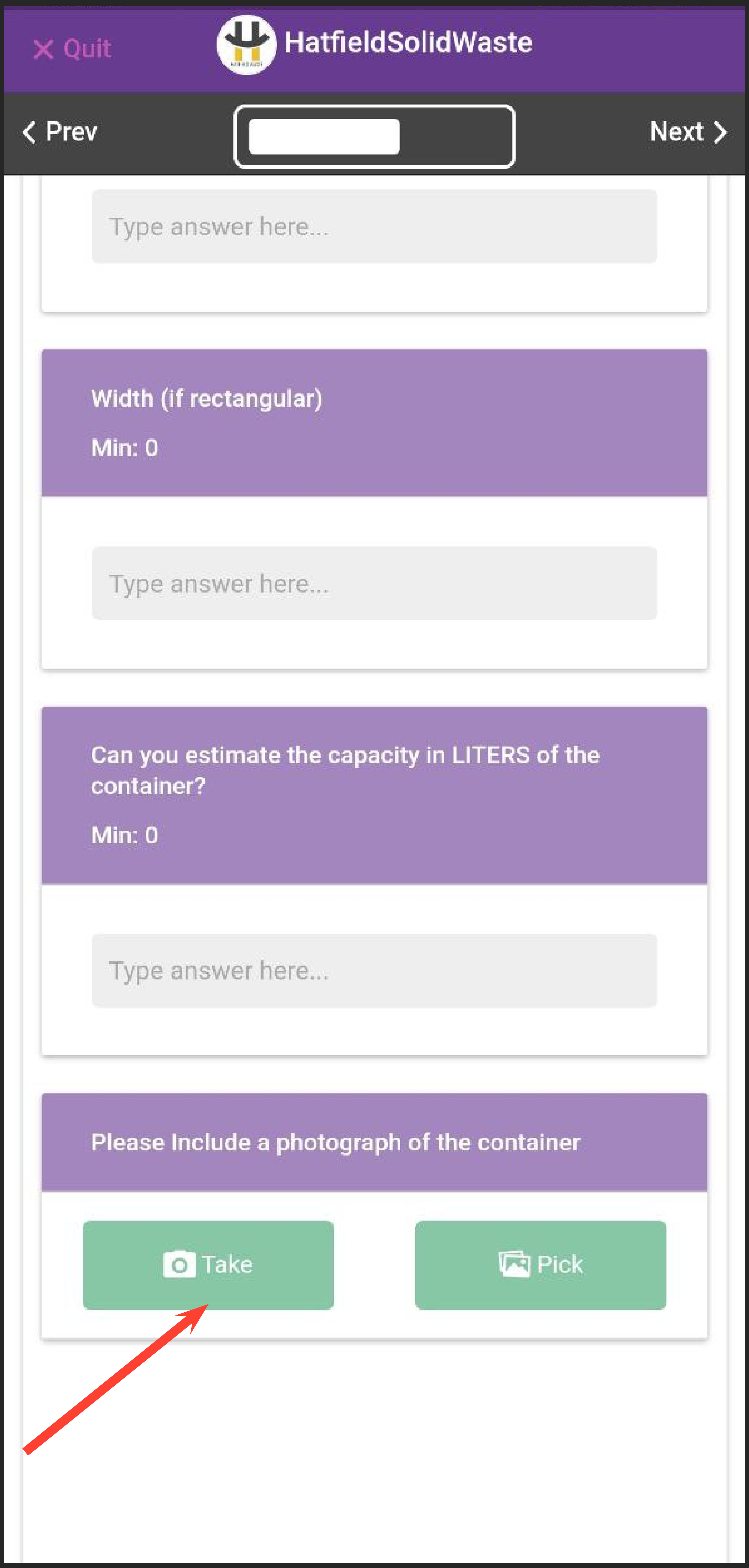
Now tap next

10.



Select the type of report you want to make, either littering place or recording a trash bin

11a.

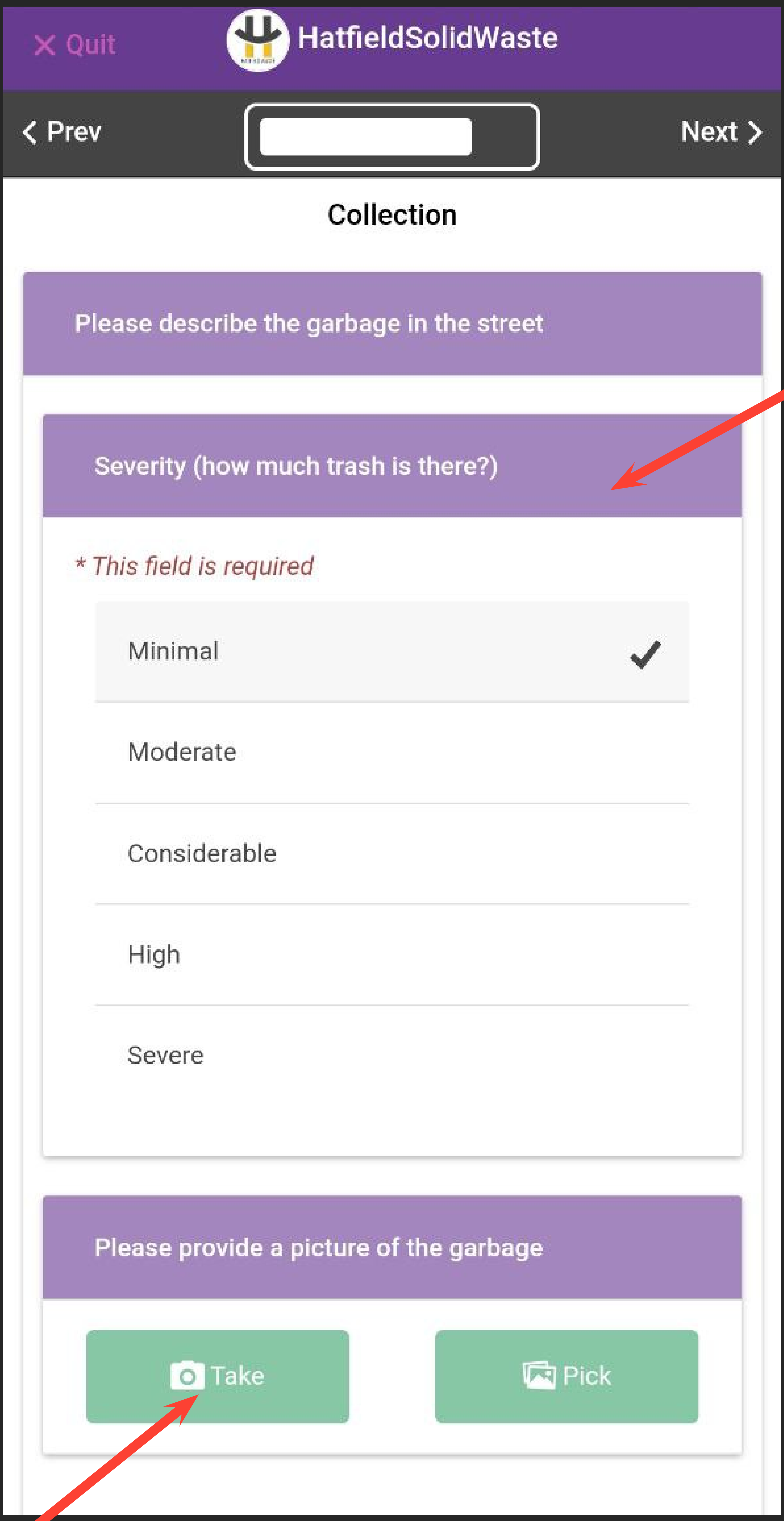


If you selected a Trash bin report, you will be asked questions about the dimensions and capacity. This are not mandatory, but would be great to have!

You can also upload pictures of the bin.

When you are done, tap next

11b.



If you selected a Littering place report, you will be asked questions about the amount of trash in the floor.

You can also upload pictures of the bin.

When you are done, tap next

11b. Minimal

Take a Look at the examples

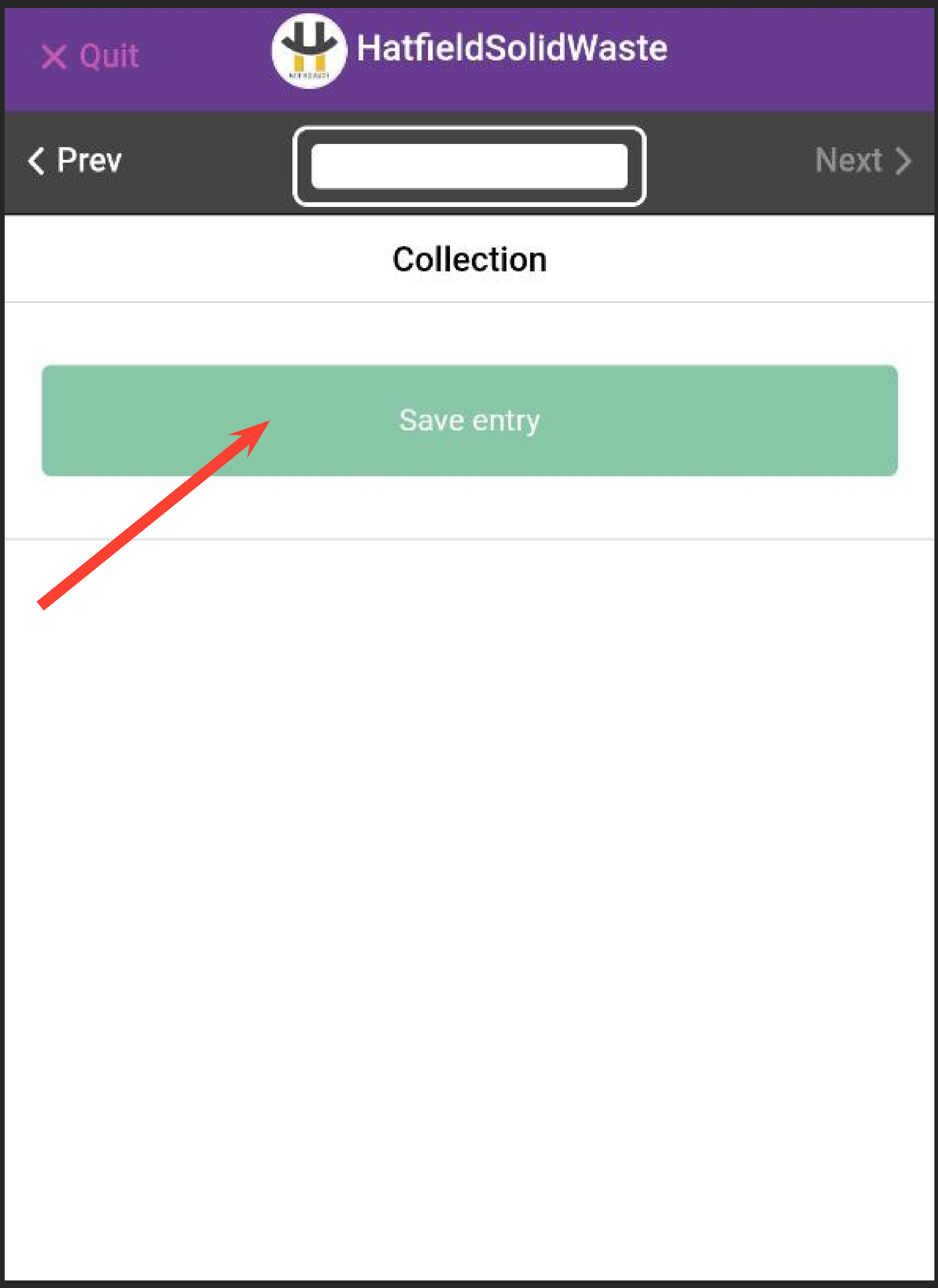
11b. MODE-RATE

Take a look at the examples

11b. SEVERE

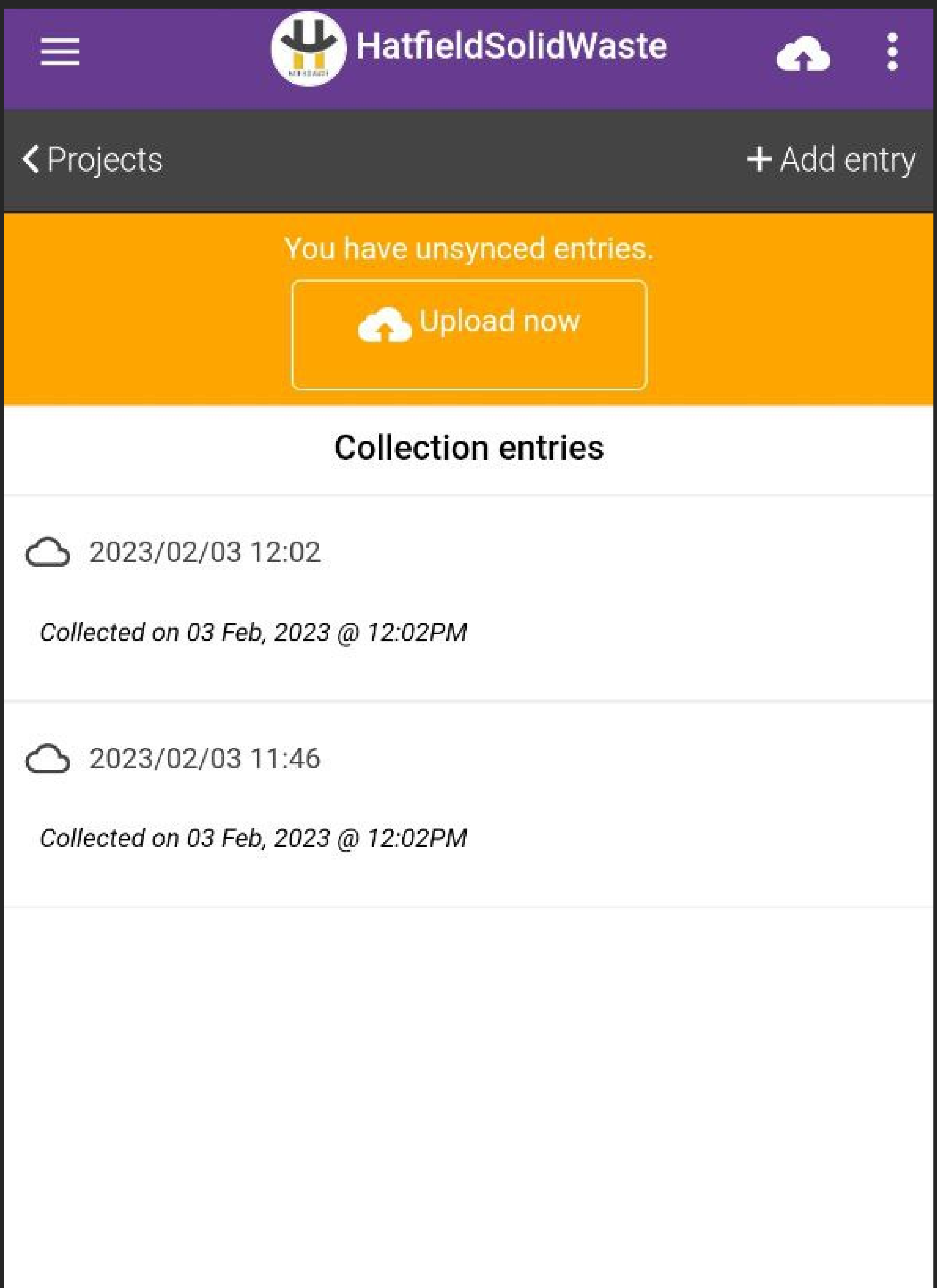
Take a look at the examples

12.



Now that you finish your first report **tap on save entry**

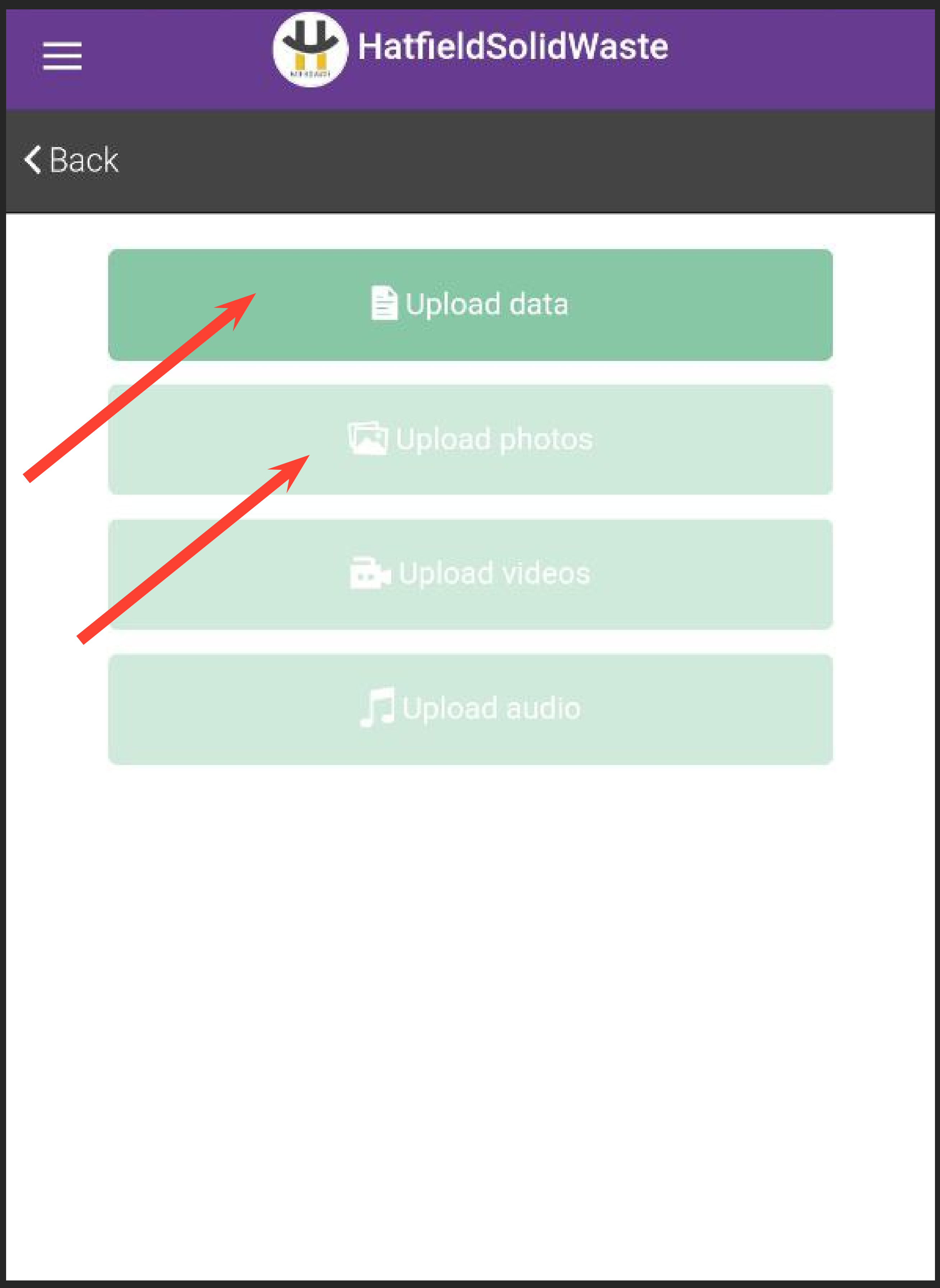
13.



To upload your entries tap the upload now button

You can have several records uploaded at the same time, try to upload every 5 or 10 entries

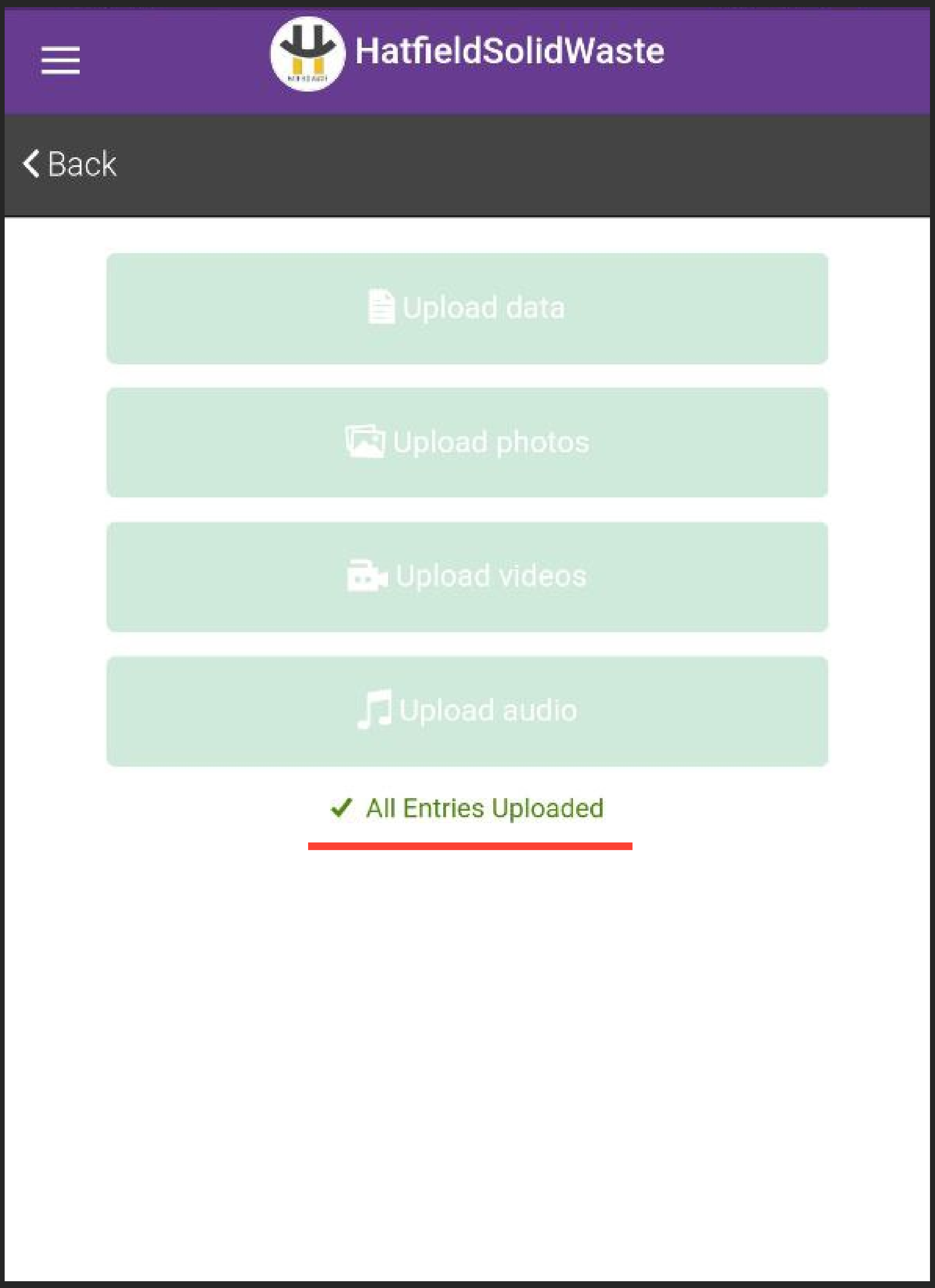
14.



Tap on upload data and wait for it to be send to the server.

If you took pictures, please also upload them.

15.



When all the information has been uploaded you will get this message.

Q: Do you have any question?

Contact us via e-mail (i.l.cardenasleon@student.utwente.nl) or whatsapp (https://wa.me/message/WKXZHS6LSIXKL1)

11.2. Stakeholders Pairwise Comparison

11.2.1. Power Relationship

	PAIRWISE COMPARISON											
POWER RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker
Business and Offices	1	1/3	1/7	1/7	1	1	1/7	1	1	1	1/3	5
Collection Companies	3	1	1/7	1/3	1/3	1/7	1/5	1/3	5	1/5	1	7
Department of Forestry Fisheries and Environment	7	7	1	5	7	9	5	3	7	5	7	9
Improvement District	7	3	1/5	1	3	1/3	1/5	1/3	7	3	1/3	7
Industrial Parks	1	3	1/7	1/3	1	1	1/5	1	1	1	1/3	5
Landfill Operators	1	7	1/9	3	1	1	1/5	3	3	1	1/3	9
Municipality	7	5	1/5	5	5	5	1	7	7	3	5	7
Real State Agencies	1	3	1/3	3	1	1/3	1/7	1	5	1	1	1
Residents	1	1/5	1/7	1/7	1	1/3	1/7	1/5	1	1	5	5
University Institution	1	5	1/5	1/3	1	1	1/3	1	1	1	1	9
Ward councillor	3	1	1/7	3	3	3	1/5	1	1/5	1	1	7
Waste picker	1/5	1/7	1/9	1/7	1/5	1/9	1/7	1	1/5	1/9	1/7	1

STANDARDIZED MATRIX													
POWER RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker	Weight
Business and Offices	3.0%	0.9%	5.0%	0.7%	4.1%	4.5%	1.8%	5.0%	2.6%	5.5%	1.5%	6.9%	3.46%
Collection Companies	9.0%	2.8%	5.0%	1.6%	1.4%	0.6%	2.5%	1.7%	13.0%	1.1%	4.4%	9.7%	4.41%
Department of Forestry Fisheries and Environment	21.1%	19.6%	34.8%	23.3%	28.5%	40.4%	63.3%	15.1%	18.2%	27.3%	31.1%	12.5%	27.95%
Improvement District	21.1%	8.4%	7.0%	4.7%	12.2%	1.5%	2.5%	1.7%	18.2%	16.4%	1.5%	9.7%	8.74%
Industrial Parks	3.0%	8.4%	5.0%	1.6%	4.1%	4.5%	2.5%	5.0%	2.6%	5.5%	1.5%	6.9%	4.22%
Landfill Operators	3.0%	19.6%	3.9%	14.0%	4.1%	4.5%	2.5%	15.1%	7.8%	5.5%	1.5%	12.5%	7.83%
Municipality	21.1%	14.0%	7.0%	23.3%	20.4%	22.5%	12.7%	35.2%	18.2%	16.4%	22.2%	9.7%	18.56%
Real State Agencies	3.0%	8.4%	11.6%	14.0%	4.1%	1.5%	1.8%	5.0%	13.0%	5.5%	4.4%	1.4%	6.15%
Residents	3.0%	0.6%	5.0%	0.7%	4.1%	1.5%	1.8%	1.0%	2.6%	5.5%	22.2%	6.9%	4.57%
University Institution	3.0%	14.0%	7.0%	1.6%	4.1%	4.5%	4.2%	5.0%	2.6%	5.5%	4.4%	12.5%	5.70%
Ward councillor	9.0%	2.8%	5.0%	14.0%	12.2%	13.5%	2.5%	5.0%	0.5%	5.5%	4.4%	9.7%	7.02%
Waste picker	0.6%	0.4%	3.9%	0.7%	0.8%	0.5%	1.8%	5.0%	0.5%	0.6%	0.6%	1.4%	1.40%

11.2.2. Urgency Relationship

PAIRWISE COMPARISON

URGENCY RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker
Business and Offices	1	1	5	1/5	1	9	1/3	1	1	1	1	7
Collection Companies	1	1	5	1/3	1/7	5	1/5	1	1/9	1/7	1/7	5
Department of Forestry Fisheries and Environment	1/5	1/5	1	1/9	1/3	7	1/7	1/3	1/7	1/5	1/3	3
Improvement District	5	3	9	1	3	7	1	5	1	1	1	5
Industrial Parks	1	7	3	1/3	1	3	1	1	1	1	1	3
Landfill Operators	1/9	1/5	1/7	1/7	1/3	1	1/7	1/3	1/9	1/7	1/7	7
Municipality	3	5	7	1	1	7	1	7	1	1	1	7
Real State Agencies	1	1	3	1/5	1	3	1/7	1	1/5	1/3	1/5	1
Residents	1	9	7	1	1	9	1	5	1	1/3	1/7	7
University Institution	1	7	5	1	1	7	1	3	3	1	1	7
Ward councillor	1	7	3	1	1	7	1	5	7	1	1	7
Waste picker	1/7	1/5	1/3	1/5	1/3	1/7	1/7	1	1/7	1/7	1/7	1

STANDARDIZED MATRIX

URGENCY RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker	Weight
Business and Offices	6.5%	2.4%	10.3%	3.1%	9.0%	13.8%	4.7%	3.3%	6.4%	13.7%	14.1%	11.7%	8.23%
Collection Companies	6.5%	2.4%	10.3%	5.1%	1.3%	7.7%	2.8%	3.3%	0.7%	2.0%	2.0%	8.3%	4.36%
Department of Forestry Fisheries and Environment	1.3%	0.5%	2.1%	1.7%	3.0%	10.7%	2.0%	1.1%	0.9%	2.7%	4.7%	5.0%	2.98%
Improvement District	32.4%	7.2%	18.6%	15.3%	26.9%	10.7%	14.1%	16.3%	6.4%	13.7%	14.1%	8.3%	15.33%
Industrial Parks	6.5%	16.8%	6.2%	5.1%	9.0%	4.6%	14.1%	3.3%	6.4%	13.7%	14.1%	5.0%	8.72%
Landfill Operators	0.7%	0.5%	0.3%	2.2%	3.0%	1.5%	2.0%	1.1%	0.7%	2.0%	2.0%	11.7%	2.30%
Municipality	19.4%	12.0%	14.4%	15.3%	9.0%	10.7%	14.1%	22.8%	6.4%	13.7%	14.1%	11.7%	13.64%
Real State Agencies	6.5%	2.4%	6.2%	3.1%	9.0%	4.6%	2.0%	3.3%	1.3%	4.6%	2.8%	1.7%	3.94%
Residents	6.5%	21.6%	14.4%	15.3%	9.0%	13.8%	14.1%	16.3%	6.4%	4.6%	2.0%	11.7%	11.31%
University Institution	6.5%	16.8%	10.3%	15.3%	9.0%	10.7%	14.1%	9.8%	19.1%	13.7%	14.1%	11.7%	12.59%
Ward councillor	6.5%	16.8%	6.2%	15.3%	9.0%	10.7%	14.1%	16.3%	44.6%	13.7%	14.1%	11.7%	14.91%
Waste picker	0.9%	0.5%	0.7%	3.1%	3.0%	0.2%	2.0%	3.3%	0.9%	2.0%	2.0%	1.7%	1.68%

11.2.3. Legitimacy Relationship

PAIRWISE COMPARISON

LEGITIMACY RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker
Business and Offices	1	1	3	1	1	5	1/3	3	1	1	3	1
Collection Companies	1	1	3	1/3	1	5	1	5	1/3	5	1/5	7
Department of Forestry Fisheries and Environment	1/3	1/3	1	1	1/3	3	1	5	1/7	1	1	9
Improvement District	1	3	1	1	1	5	1	3	1	1/3	1	7
Industrial Parks	1	1	3	1	1	5	1	1	1	1	1/3	7
Landfill Operators	1/5	1/5	1/3	1/5	1/5	1	1/7	1/5	1/7	1/7	1/7	7
Municipality	3	1	1	1	1	7	1	5	1	1/3	1	7
Real State Agencies	1/3	1/5	1/5	1/3	1	5	1/5	1	1/7	1	1/3	3
Residents	1	3	7	1	1	7	1	7	1	1	5	1
University Institution	1	1/5	1	3	1	7	3	1	1	1	1	5
Ward councillor	1/3	5	1	1	3	7	1	3	1/5	1	1	7
Waste picker	1	1/7	1/9	1/7	1/7	1/7	1/7	1/3	1	1/5	1/7	1

STANDARDIZED MATRIX

LEGITIMACY RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker	Weight
Business and Offices	8.9%	6.2%	13.9%	9.1%	8.6%	8.8%	3.1%	8.7%	12.6%	7.7%	21.2%	1.6%	9.19%
Collection Companies	8.9%	6.2%	13.9%	3.0%	8.6%	8.8%	9.2%	14.5%	4.2%	38.4%	1.4%	11.3%	10.70%
Department of Forestry Fisheries and Environment	3.0%	2.1%	4.6%	9.1%	2.9%	5.3%	9.2%	14.5%	1.8%	7.7%	7.1%	14.5%	6.80%
Improvement District	8.9%	18.7%	4.6%	9.1%	8.6%	8.8%	9.2%	8.7%	12.6%	2.6%	7.1%	11.3%	9.17%
Industrial Parks	8.9%	6.2%	13.9%	9.1%	8.6%	8.8%	9.2%	2.9%	12.6%	7.7%	2.4%	11.3%	8.45%
Landfill Operators	1.8%	1.2%	1.5%	1.8%	1.7%	1.8%	1.3%	0.6%	1.8%	1.1%	1.0%	11.3%	2.25%
Municipality	26.8%	6.2%	4.6%	9.1%	8.6%	12.3%	9.2%	14.5%	12.6%	2.6%	7.1%	11.3%	10.39%
Real State Agencies	3.0%	1.2%	0.9%	3.0%	8.6%	8.8%	1.8%	2.9%	1.8%	7.7%	2.4%	4.8%	3.91%
Residents	8.9%	18.7%	32.3%	9.1%	8.6%	12.3%	9.2%	20.3%	12.6%	7.7%	35.3%	1.6%	14.71%
University Institution	8.9%	1.2%	4.6%	27.2%	8.6%	12.3%	27.7%	2.9%	12.6%	7.7%	7.1%	8.1%	10.74%
Ward councillor	3.0%	31.1%	4.6%	9.1%	25.7%	12.3%	9.2%	8.7%	2.5%	7.7%	7.1%	11.3%	11.02%
Waste picker	8.9%	0.9%	0.5%	1.3%	1.2%	0.3%	1.3%	1.0%	12.6%	1.5%	1.0%	1.6%	2.68%

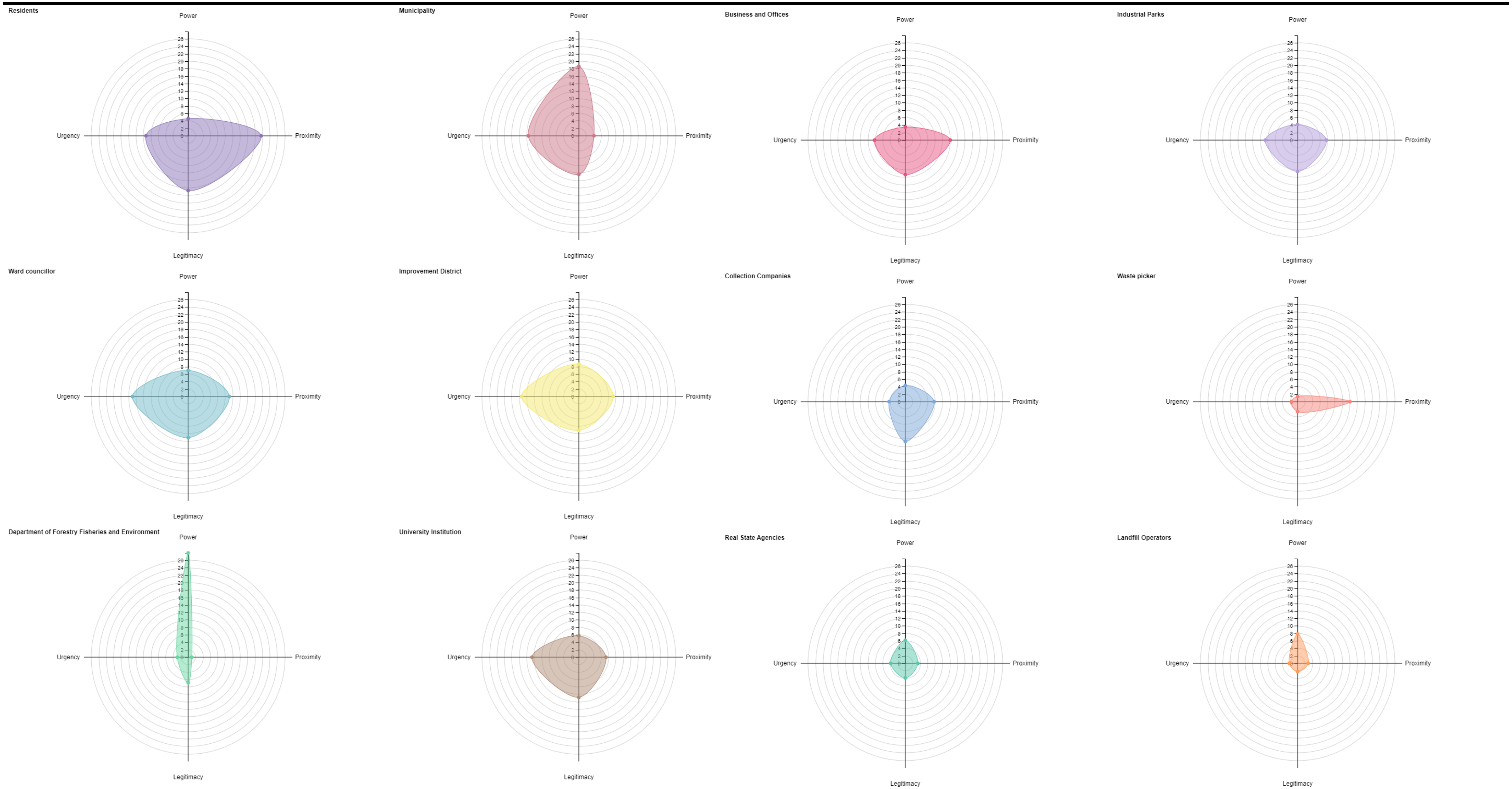
11.2.4. Proximity Relationship

PAIRWISE COMPARISON

PROXIMITY RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker
Business and Offices	1	1	9	7	1	5	3	1	1	1	3	1
Collection Companies	1	1	9	3	1	5	3	3	1/5	1/5	1/5	1
Department of Forestry Fisheries and Environment	1/9	1/9	1	1/7	1/7	1/7	1/9	1/7	1/7	1/7	1/9	1/9
Improvement District	1/7	1/3	7	1	1/5	5	7	7	1/3	5	1	1
Industrial Parks	1	1	7	5	1	5	5	1	1/5	1	1/7	1/5
Landfill Operators	1/5	1/5	7	1/5	1/5	1	3	1	1/7	1/7	1/7	1/5
Municipality	1/3	1/3	9	1/7	1/5	1/3	1	5	1/5	1/3	1	1/3
Real State Agencies	1	1/3	7	1/7	1	1	1/5	1	1/9	1	1/7	1/9
Residents	1	5	7	3	5	7	5	9	1	7	7	1
University Institution	1	5	7	1/5	1	7	3	1	1/7	1	1/3	1/5
Ward councillor	1/3	5	9	1	7	7	1	7	1/7	3	1	1/3
Waste picker	1	1	9	1	5	5	3	9	1	5	3	1

STANDARDIZED MATRIX

PROXIMITY RELATIONSHIP	Business and Offices	Collection Companies	Department of Forestry Fisheries and Environment	Improvement District	Industrial Parks	Landfill Operators	Municipality	Real State Agencies	Residents	University Institution	Ward councillor	Waste picker	Weight
Business and Offices	12.3%	4.9%	10.2%	32.1%	4.4%	10.3%	8.7%	2.2%	21.7%	4.0%	17.6%	15.4%	11.99%
Collection Companies	12.3%	4.9%	10.2%	13.7%	4.4%	10.3%	8.7%	6.6%	4.3%	0.8%	1.2%	15.4%	7.75%
Department of Forestry Fisheries and Environment	1.4%	0.5%	1.1%	0.7%	0.6%	0.3%	0.3%	0.3%	3.1%	0.6%	0.7%	1.7%	0.94%
Improvement District	1.8%	1.6%	8.0%	4.6%	0.9%	10.3%	20.4%	15.5%	7.2%	20.1%	5.9%	15.4%	9.31%
Industrial Parks	12.3%	4.9%	8.0%	22.9%	4.4%	10.3%	14.6%	2.2%	4.3%	4.0%	0.8%	3.1%	7.66%
Landfill Operators	2.5%	1.0%	8.0%	0.9%	0.9%	2.1%	8.7%	2.2%	3.1%	0.6%	0.8%	3.1%	2.82%
Municipality	4.1%	1.6%	10.2%	0.7%	0.9%	0.7%	2.9%	11.1%	4.3%	1.3%	5.9%	5.1%	4.07%
Real State Agencies	12.3%	1.6%	8.0%	0.7%	4.4%	2.1%	0.6%	2.2%	2.4%	4.0%	0.8%	1.7%	3.40%
Residents	12.3%	24.6%	8.0%	13.7%	22.0%	14.4%	14.6%	19.9%	21.7%	28.2%	41.0%	15.4%	19.65%
University Institution	12.3%	24.6%	8.0%	0.9%	4.4%	14.4%	8.7%	2.2%	3.1%	4.0%	2.0%	3.1%	7.31%
Ward councillor	4.1%	24.6%	10.2%	4.6%	30.8%	14.4%	2.9%	15.5%	3.1%	12.1%	5.9%	5.1%	11.11%
Waste picker	12.3%	4.9%	10.2%	4.6%	22.0%	10.3%	8.7%	19.9%	21.7%	20.1%	17.6%	15.4%	13.98%



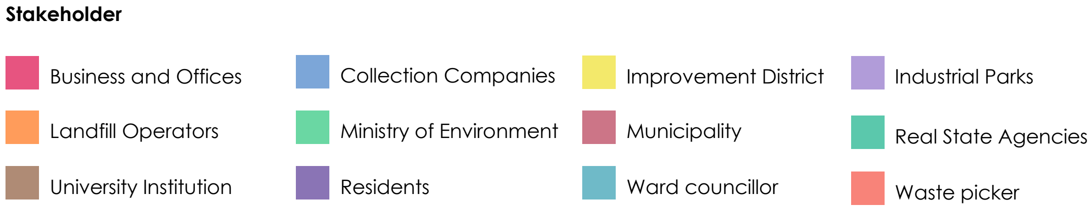


***Figure** 51. Stakeholder attribute relationship. Values are calculated in percentage proportion of each attribute.*

11.3. Digital Twin Evaluation Survey

***Table** 13. Digital Twin evaluation survey*

#	Category	Indicator	Question	Domains
1	Welcome Message		Dear Participant, Thank you for taking the time to participate in this survey focused on evaluating the effectiveness and user experience of our **Solid waste management Digital Twin dashboard**. Your valuable feedback will help us enhance and refine the Digital Twin to better meet the needs of waste management. The purpose of this survey is to gather insights about various aspects of the dashboard, including **user-friendliness, interactivity, spatial interface, learnability, effectiveness, and communicative value**. Your honest opinions and observations will play a crucial role in shaping the future development of the dashboard. **Please note that all responses provided in this survey will be kept strictly confidential and used solely for research purposes. We do not collect personal information, and all answers are anonymous.** The survey consists of Likert scale statements where you will be asked to rate your agreement level with each statement on a scale of 1 to 5. Additionally, there will be opportunities for you to provide any specific comments or suggestions to further improve the dashboard. The estimated time to complete the survey is approximately **5 minutes**. Thank you once again for your participation and valuable input. Your contribution is highly appreciated. Let's begin the survey by clicking the "**Next**" button below.	
2	Classification	Stakeholder Type	Within the Waste Management System, I identify myself as a member of...	Business and Offices Collection Companies Department of Forestry Fisheries and Environment Improvement District Industrial Parks Landfill Operators Municipality Real State Agencies Residents University Institution Ward councillor Waste picker
3	User Friendliness and Interactivity	Ease of Use	1. I find it simple to perform tasks and actions within the dashboard.	1 = Strongly Disagree 2= Disagree 3 = Neither agree or disagree 4 = Agree 5 = Strongly Agree
4			2. The layout and design of the dashboard are intuitive and visually appealing.	
5			3. Overall, I find the dashboard user-friendly and enjoyable to use.	
6		Data Exploration	1. The dashboard allows me to interact with the data and explore different variables.	
7			2. I can customize the dashboard to display the specific information I need.	
8			3. The interactive features of the dashboard enhance my understanding of the data.	
9	Spatial Interface	Map Visualization	1. The map visualization effectively represents the location of containers and collection routes.	
10			2. The spatial interface of the dashboard provides a clear overview of the waste management system.	
11			3. The visual representation of containers and routes helps me better comprehend the geographical aspect of waste management.	
12	Interactivity	Ease of Learning	1. I feel confident in my ability to effectively use the dashboard after minimal guidance.	
13			2. The dashboard offers informative descriptions of its various elements and functions.	

#	Category	Indicator	Question	Domains
14			3. The learning curve for using the dashboard was minimal, and I could easily adapt to it.	
15	Consensus, Effectiveness and Communicative Value	Data Accuracy and Decision-making Support	1. The dashboard accurately presents the current status of container saturation and waste collection needs.	
16			2. The dashboard effectively communicates the amount of waste in the containers and waste production by building class.	
17			3. The dashboard enables tracking and monitoring of waste collection progress and performance metrics.	
18			4. Overall, the dashboard efficiently fulfills its intended purpose of managing solid waste and optimizing collection processes.	
19		Stakeholder Communication and Collaboration	1. The information provided in the dashboard helps me make informed decisions regarding waste management.	
20			2. The dashboard provides valuable insights and information for stakeholders to collaborate and address waste management challenges.	
21			3. The dashboard successfully communicates the impact of waste accumulation and collection efforts.	
22	Final Remarks	Open end questions	What did you like ?	Optional
23			What did you dislike ?	Optional
24			How can the toool be improved?	Optional

11.4. Stakeholders Demo Video

[Video Link]