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ROBOTS IN WASTE MANAGEMENT

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ABSTRACT
There are different strategies for urban waste management. At present, solutions are being sought for example to the noise that the collections cause to the inhabitants in the cities, as well as the environmental impact. The introduction of technology and particularly robots in the last time, open an opportunity to develop different applications for the robots last mile. This paper highlights and discusses properties of robotic waste collection, based on existing literature of the environmental and economic impacts of different waste collection and management systems. It explores how a robotic system could be introduced into public spaces. For this purpose, a new deployment protocol for public spaces has been developed, addressing these interactions. Surveys and personalized interviews with pedestrians in the presence of the robot in an urban center were conducted. Based on the collected data, a protocol has been designed, along with a proposed design applicable to urban centers, small towns, or isolated residential areas. Many challenges remain, including a comprehensive environmental analysis of the robotic waste collection system, and calculating the actual costs of implementation, operation, and maintenance over time.

1. INTRODUCTION

Urban waste management (Muntasir Shovon et al., 2024) is a practice that has been carried out for a long time in cities due to the importance of sanitation in preventing the spread of diseases (Moanaro Ao and Nzanthung Ngullie, 2024). Throughout history, solid waste has been handled in a simple manner, for example, using horse-drawn carts to collect the waste that accumulated in the streets and industries, and recycling those residues that could have value. Examples of this approach can be found in ancient Rome, where circular economy was valued (Brunner and Morf, 2024), and recycling was done as much as possible.

The big revolution in waste collection happened in the late 19th century with the emergence of the first steam-powered trucks, initially simple open-box carts. Later, the internal combustion engine, containers, and the establishment of routes that we are familiar with today arrived, now enhanced by the latest technologies (Di Maria et al., 2020).

Today, the amount of waste generated in cities remains a significant problem (Rossit and Nesmachnow, 2022), both from a public health and environmental perspective. One way to address this problem is through the implementation of more efficient and sustainable waste collection systems.

When comparing different methods of waste collection, including manual collection, automated waste collection using robots, and specifically last-mile robots, several advantages and disadvantages can be identified (Table 1). Manual waste collection is labor-intensive and time-consuming (Sushma et al., 2021), while automated waste collection using robots can significantly increase efficiency and reduce the need for manual labor (Raihan et al., 2020).

Underground garbage collection containers offer numerous advantages such as preventing the spread of odors and water, reducing the risk of illnesses from bacteria, saving space, enabling hygienic waste collection, and facilitating on-site waste separation (Delice et al., 2019). These systems utilize innovative features like ultraviolet disinfection to ensure cleanliness and deodorization while maintaining safety (Morakabatchian at al., 2021). Additionally, underground containers help in efficient waste collection and contribute to recycling efforts due to their compact design (Delice et al., 2019). However, some disadvantages include the initial installation costs and potential maintenance requirements associated with the complex mechanisms involved in these systems.

Last-mile robots, in particular, offer the advantage of autonomously navigating to collect waste, reducing human intervention and potentially lowering operational costs

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TABLE 1: Advantages and disadvantages of integrating robots into urban spaces.

Waste collection methods	Advantages	Disadvantages
Manual waste collection (Sushma S C et al. 2021)	Flexibility and adaptability	Labour-intensive
	Capacity to handle bulky waste	Risk of injury and exposure to hazardous substances
	Low initial cost of equipment	Inefficiency in large or densely populated areas.
	Direct human interaction and quality control	Variability in the quality of work
		Time-consuming
Mechanised Collection (Raihan N. et al.2020, Badve M. et al 2024)	High efficiency in the collection of large volumes	Require initial investment and maintenance efforts
	Reduction of manual time and effort.	Requires adequate infrastructure (wide streets, accessibility).
	Reduced exposure of staff to hazardous waste.	Emission of gaseous pollutants and noise.
	Greater consistency and reliability of service	Difficulty in areas of difficult access or complex geometries
Underground Containers (Delice E. et al. 2019,Morakabatchian M. at al. 2021)	Improved urban aesthetics.	the initial installation costs and potential maintenance requirements associated with the complex mechanisms involved in these systems
	Reduction of odours and pests.	Need for underground infrastructure.
	Increased storage capacity.	Difficulty of collection in case of system failures.
	Less frequent collection required.	Requires specific technology for harvesting.
Harvesting with Last Mile Robots(Tomitagawa, K. et al. 2024)	Autonomous operation, reduces the need for manual labour.	High cost of development and initial implementation
	Possibility of operating at non-conventional times	Limitations on carrying capacity and types of waste
	Reduced emissions and noise compared to larger vehicles.	Dependence on advanced technologies and connectivity.
	Accuracy in collection and route optimisation.	Need to adapt urban infrastructure
	Improved operational efficiency in dense urban areas	Possible technical failures and complex maintenance.
	Potentially lowering operational costs	Challenges such as energy consumption efficiency .
		Path optimization exist for waste collection robots, which can impact their overall effectiveness in waste management tasks.

(Tomitagawa et al., 2024). However, challenges such as energy consumption efficiency and path optimization exist for waste collection robots, which can impact their overall effectiveness in waste management tasks (Tomitagawa et al., 2024). Therefore, while last-mile robots offer automation benefits, considerations regarding energy efficiency and path optimization are crucial for maximizing their effectiveness in waste collection operations. This is still in the process of being studied and optimized.

Due to the current door-to-door selective waste collection (PaP) (Laso et al., 2019; Baltrocchi APD., 2024; Dotsenko et al., 2022) implemented by the Catalan Waste Agency, which involves delivering waste to the municipal service at your doorstep, it has complicated and duplicated the work of waste collection services, as well as their costs. The implementation of a home waste-collecting robot in Catalonia offers numerous advantages, such as cost reduction through a decrease in the number of collection vehicles on the streets, as well as a reduction in maintenance and operational costs. There would also be an improvement in the efficiency of the collection process and a reduction in the environmental impact of the activity, enhancing the residential landscape and reducing unpleasant odors. Currently, robots can be found in numerous controlled environments:

- Airports (Hwang et al., 2023): Robots have been used in airports to perform tasks such as floor cleaning, waste removal, baggage delivery, and passenger transportation. For example, Incheon Airport in South Korea utilizes a passenger and baggage transport robot.
- Restaurants (Molinillo et al., 2023): In some restaurants, robots are used to take orders and deliver food to tables. For instance, the Spyce restaurant in Boston features a fully automated kitchen that uses robots to prepare and serve food.
- Hospitals (Huang et al., 2023): Robots have been employed in hospitals to transport supplies and food, as well as perform cleaning and disinfection tasks. For instance, Texas Children's Hospital in Houston uses robots called Tugs to transport medications and supplies to different areas of the hospital.
- Parking lots (Soori et al., 2023): Robots have been utilized in certain parking lots for autonomous parking and retrieving of vehicles. For example, at the Volkswagen Autostadt in Wolfsburg, Germany, visitors can leave their cars in an automated parking structure called Car Towers, which uses robots to retrieve and deliver vehicles.

The evolution of urban waste management has seen significant advancements, transitioning from historical methods to modern technologies like autonomous waste-collecting robots (Liang-Bi Chen et al., 2023; Bharanikumar et al., 2022, Sushma et al., 2021). These robots offer a sustainable solution by reducing operational costs, minimizing environmental impact, and enhancing efficiency in waste collection processes. By integrating autonomous robots into urban environments, particularly in areas like Catalonia, where door-to-door waste collection systems are in place, numerous benefits can be realized, including cost reduction, improved operational efficiency, and a reduction in environmental footprint. The implementation of waste-collecting robots not only addresses the challenges of waste management but also contributes to job creation in the technology sector and promotes the adoption of sustainable technologies, marking a significant step in the robotics industry's evolution towards more complex urban applications.

These robots, equipped with artificial intelligence and robotic systems, aim to autonomously collect and dispose of garbage while monitoring waste levels and contents in smart trash cans. By utilizing technologies such as AIoT (Artificial Intelligence of Things), ROS (Robot Operating System) (Sunil and Shanavas, 2023), image sensors, and ultrasonic sensors, these robots can navigate designated areas, detect trash, and efficiently manage waste disposal processes, contributing to cleaner environments and improved waste management practices (Gupta et al., 2022). The ability of a waste-collecting robot to operate in these challenging environments requires a combination of technical skills, such as autonomous navigation, obstacle detection, and coordination of multiple simultaneous tasks, as well as excellent adaptability. The robot must be capable of planning efficient collection routes, safely maneuvering through streets and sidewalks, accurately picking up the waste, and depositing it in the appropriate location (Azza et al., 2023). Additionally, it must interact safely and respectfully with citizens, given its operation in public settings. This article will explore these interactions, focusing on how the robot engages with the city and its residents.

Research questions:

What environmental and social analyses have been conducted on garbage collection robots? What challenges and intersections arise when introducing last-mile garbage collection robots in cities, particularly in terms of pedestrian reactions, public space sharing preferences, and potential physical conflicts with existing infrastructures? What protocols should be followed to minimize any inconvenience during their integration?

The study aims to address these research questions by conducting a comprehensive systematic review of last-mile waste collection robots, including economic, environmental (Life Cycle Assessment), and social analyses, and proposing a new framework for implementing a robotic waste collection system in urban areas. The literature mainly addresses technology and human-robot interaction (Tuli et al., 2022; Fischer et al., 2022; Hwang et al., 2007), but research on how these robots interact with urban infrastructure is lacking. This study aims to design an innovative robot tailored for urban environments, particularly residential complexes with shared spaces and waste collection points. It will also examine the robot's interaction with city infrastructure and residents, focusing on potential physical conflicts with existing structures. Additionally, the study will compare door-to-door and robotic waste collection systems to propose a new protocol for integrating these robots into urban centers, promoting widespread adoption.

2. METHODOLOGIES

This paper offers a comprehensive systematic bibliographic review focusing on three key aspects. Firstly, it examines the diverse range of robots developed for last-mile waste collection, incorporating economic, environmental (LCA), and social analyses. Secondly, it proposes a framework for the implementation process of a last-mile robotic system within urban areas. Lastly, it presents a novel robot proposal tailored for urban environments with residential complexes or blocks featuring shared spaces and waste collection points.

In the systematic literature review, we explore the various existing robots that have been developed specifically for last-mile waste collection. This includes examining their functionalities, capabilities, and performance in real-world scenarios. We analyze the navigation systems used by these robots to maneuver through complex urban environments, their ability to detect and avoid obstacles, and their collection mechanisms. We also assess their efficiency in terms of time and energy consumption, as well as their adaptability to different types of waste.

For the purpose of conducting this comprehensive review, we will utilize the extensive resources available within the Web of Science (WOS) database. This database offers a vast collection of peer-reviewed literature spanning various disciplines, ensuring a thorough and in-depth analysis of the relevant research findings.

To assess the current state-of-the-art in last-mile waste-collecting robots, a comprehensive literature review was conducted using the Web of Science database (2023). The search utilized the terms "trash collection robots," "autonomous waste collection," "robotic waste collection," and "waste management robots," combined with the Boolean operator "OR" to retrieve relevant articles. As depicted in Figure 1, although research in this field began in 1992, there has been a significant increase in published studies over the past four years.

When we delve deeper into the analysis of the results, it becomes evident that among the six most productive countries, China, the United States, and India significantly outshine the rest. Spain, as the leading European nation in scientific production within this context, holds the fourth position.

If we look at the document types, we can see that there are 211 journal articles, 144 proceeding papers, and 17 reviews, resulting in a total of 369 documents. When filtering by these three document types, we reduce the search to 369 results.

If we further refine the search by adding "AND LCA" to consider the environmental impact through a life cycle assessment, we narrow down our search to 205 documents. Then, if we select only articles and literature reviews, we

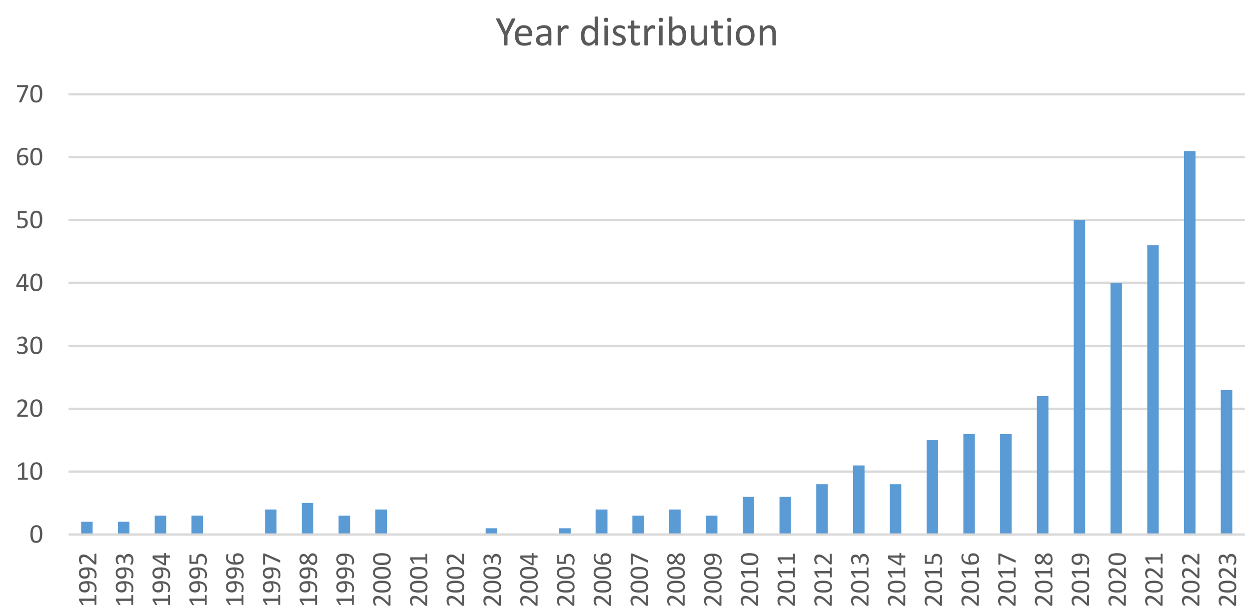

FIGURE 1: Year distribution of the number of publications on waste-collecting robots.

are left with 141 documents. From these, we can take the top 5 most cited and the 5 most recent, which are presented in Table 2.

In these articles, we can see that digitization and artificial intelligence are considered important aspects in waste management and the involvement of waste-collecting robots. The circular economy is mentioned as a key approach to waste management and the application of advanced technology. Environmental sustainability is a recurring theme, focusing on waste management as well as other related areas such as recycling and reverse logistics. Challenges and opportunities associated with the implementation of waste-collecting robots are mentioned, such as the need to adapt to different contexts and the automation of tasks. Furthermore, the exploitation of waste management in specific contexts is discussed, including the generation of alternative fuels and biogas from waste materials, among other elements.

If we analyze the 17 articles that are reviews and cover the entire period up to the present day, we can highlight that the first article discusses how to digitize the waste management value chain, always considering the circular economy. The second article highlights artificial intelligence as a key factor in waste management in cities and presents a use case in a smart city. The third article, found in Table 2, focuses on waste classification and discusses the challenges and opportunities that arise. The fourth article presents a case study in China and explains the characteristics of waste management in a rural area. The sixth article discusses the informal management of urban waste in eight Latin American countries. The thirteenth article discusses motion control and forces of robots, although it could be applicable to any similar application, it is very specific about the functioning and autonomous movement of the robot. Lastly, the seventeenth article presents an analysis of digitalization driven by urban circular metabolism and examines circular city initiatives.

We made a proposed implementation protocol for said last mile robot dedicated to urban waste collection. To define the protocol, our approach draws upon existing literature on robot integration and leverages insights from previous experiences documented by the Institute of Robotics and Industrial Informatics (IRI) at the Universitat Politècnica de Catalunya (UPC).

To gauge user acceptance, in the last stage of the protocol, we employed two strategies. Firstly, we conducted a survey to enable quantitative analysis of the level of user acceptance regarding the integration of robots into urban areas for waste collection. This survey, hosted on Google Forms, was initially distributed through the researchers' social networks, targeting individuals within their respective circles. Subsequently, the Esplugues de Llobregat city council, a participating entity in the project, was approached to disseminate the survey on the city hall website, thereby reaching the local populace for whom the system is intended. The questionnaire comprised six sections encompassing a total of 26 questions. These sections addressed various aspects such as users' perceptions of the robot's interaction with citizens, the tasks performed by the robot, the necessary infrastructures to support last-mile distribution robots (including connectivity, data management, monitoring, and energy recharging), the design and organization of urban public space, and the sustainability implications of introducing distribution robots into urban environments. To enhance respondents' engagement and comprehension, the questionnaire incorporated videos and images. The survey questionnaire is accessible via the following link: https://forms.gle/9ojMG6P1rCAYNbodA

Another strategy involved conducting structured interviews in two distinct environments:

- The first set of interviews took place in controlled areas over several days. During this phase, the robots were deployed across the university campus, where

TABLE 2: Most cited and most recent paper about Smart Trash Robot System. Literature reviews on last-mile garbage robots.

Title	Authors	Journal
Most cited and most recent paper about Smart Trash Robot System		
Smart technologies for collection and classification of electronic waste	Ada, E; Ilter, HK; Kazancoglu, Y	International Journal Of Quality & Reliability Management (2023)
The impacts of autonomous vehicles on local government budgeting and finance: case of solid waste collection	clark, by	National Tax Journal(2020)
Smart Trash Can Robot System with Integration of Internet of Things and Mobile Applications	Chang, BR; Tsai, HF; Yin, TK	Sensors And Materials (2019)
Stb: Child-dependent Sociable Trash Box	Yamaji, Y; T; Okada, M	International Journal Of Social Robotics (2011)
Digitalisation and intelligent robotics in value chain of circular economy oriented waste management - A review	Sarc, R; Curtis, A; Pomberger, R	Waste Management(2019). Citations 151
Public willingness to pay and participate in domestic waste management in rural areas of China	Han, ZY; Zeng, D; Mou, ZS	Resources Conservation And Recycling. Citations 54
Does performance evaluation help public managers? A Balanced Scorecard approach in urban waste services	Guimaraes, B;Simoes, P and Marques, RC	Journal Of Environmental Management(2010). Citations 54
A mobile robot based system for fully automated thermal 3D mapping	Borrmann, D; Nuchter, A;; Velagic, J	| Advanced Engineering Informatics (2014). Citations 53
Optimal Route Recommendation for Waste Carrier Vehicles for Efficient Waste Collection: A Step Forward Towards Sustainable Cities	Ahmad, S; Imran; Kim, D	Ieee Access (2020) Citations 30
Literature reviews on last-mile garbage robots		
1.-Digitalisation and intelligent robotics in value chain of circular economy oriented waste management- A review	Sarc, R; Curtis, A; Pomberger, R	Waste Management (2019)
2-Artificial intelligence for waste management in smart cities: a review	Fang, BB; Yu, JC; Yap, PS	Environmental Chemistry Letters(2023)
3.-A state-of-the-art review on robotics in waste sorting: scope and challenges	Satav, AG; Kubade, S; Pawar, A	International Journal Of Interactive Design And Manufacturing - Ijidem (2023)
4.-Characteristics and management modes of domestic waste in rural areas of developing countries: a case study of China	Han, ZY;Ye, CW; Shi, GZ	Environmental Science And Pollution Research (2019)
6.-The Role of Informal Waste Management in Urban Metabolism: A Review of Eight Latin American Countries	Espinosa-Aquino, B; Durany, XG and Vargas, RQ	Sustainability (2023)
13.-Hybrid motion/force control: a review	Ortenzi, V; Stolkin, R; Mistry, M	Advanced Robotics (2017)
17.-Digitalisation driven urban metabolism circularity: A review and analysis of circular city initiatives	D'Amico, G; Arbolino, R; Ioppolo, G	Land Use Policy (2022)

students, professors, administrative staff, maintenance workers, security personnel, and cleaning staff were approached for interviews. Although this initial approach resulted in a somewhat biased sample, with the majority comprising students from a technological university, it provided valuable insights into the perspectives of the younger generation.

- The second approach to assess robot acceptance involved traveling to Esplugues de Llobregat, a city chosen for its diverse urban environment. Here, the research team transported the robot to various locations within the city and conducted interviews with pedestrians encountered along the way. The interview questions mirrored those used in the survey, facilitating data extraction and comparison with quantitative analysis. Despite maintaining a structured format, participants were encouraged to openly express any concerns, ensuring comprehensive feedback.
- Finally, based on the findings from the literature review and the feedback of the users, we propose a specific robot design tailored for urban developments with communal areas and waste collection points (Saragih et al., 2023). This robot is designed to operate within the confines of the urbanization, collecting waste from designated collection points. We outline the key features of our proposed robot, including its size, maneuverability, collection mechanism, and navigation system. We also discuss the potential benefits of implementing such a robot in terms of cost reduction, improved efficiency, and enhanced cleanliness in communal areas.

3. RESULTS AND DISCUSSION

When analyzed together all the papers (Table 2), we see the importance given to digitalization, artificial intelligence, and other advanced technologies in waste management and the development of more efficient waste-collecting robots. Most of the articles mention the circular economy as a key approach to waste management and how waste-collecting robots can play a role in transitioning to a circular economy model. The importance of environmental sustainability in waste management and the development of environmentally friendly technologies and robots is addressed. Waste-collecting robots (Chen et al., 2023). are considered efficient and automated tools for waste collection and sorting, which can increase efficiency and reduce costs associated with waste management. Challenges and opportunities associated with the implementation of waste-collecting robots are highlighted, such as autonomous navigation in complex urban environments, safe interaction with citizens, and coordination of multiple simultaneous tasks. We have also seen examples of waste management in specific contexts, such as rural areas in developing countries or in smart cities, emphasizing the need to adapt waste-collecting robots to different environments and requirements.

Andreasi Bassi et al. (2017) compare the environmental impacts of household waste management in seven European countries (Germany, Denmark, France, the UK, Italy, Poland, and Greece), highlighting the benefits and challenges of different waste management strategies (as we previously present in table 1). Notably, Germany shows the best environmental performance, with high recycling rates and minimal landfilling. Recycling generally yields the largest environmental benefits, particularly for paper, metals, and glass, while waste-to-energy (WtE) plants can either contribute to environmental savings or loads, depending on their efficiency and the energy they replace. Denmark stands out for achieving significant environmental savings through energy recovery due to its extensive district heating network. However, France's high recycling rates are offset by the environmental burden from WtE plants, and Greece and Poland show high environmental impacts due to heavy reliance on landfilling. The study emphasizes that as Europe moves away from landfilling, a shift in focus is needed from managing waste inputs to maximizing the value of recovered materials and energy outputs. It also notes that increasing recycling rates does not always correlate with better environmental performance, depending on national contexts and technological factors.

In parallel with the information search for the design of the waste collection robot, a protocol for the deployment of these robots in public spaces has been developed. There are numerous studies examining the logistical integration of last-mile robots, primarily for parcel delivery (Demir et al., 2022; Hyeong et al., 2021; Deloite, 2023). Conversely, some studies focus exclusively on robot design (Boysen et al., 2021; Park et al., 2023; Burde et al., 2023). Other researchers focus on making deliveries more sustainable and optimizing resources to the maximum (Aljohani and Thompson, 2019; Ranieri et al., 2018), including authors who analyze the interactions between robots, people, and public space (Puig-Pey et al., 2023). However, there is still a need for subsequent adaptation of the robot or public space to ensure the seamless integration of the robot. Therefore, we propose in this paper a new protocol with different phases for its proper implementation, taking into account not only the interaction with public space but also with people and current mobility systems.

Before proceeding to analyze the integration of a robot within the urban space and recognizing its technical viability with necessary adaptations yet to be made, we have assessed its environmental sustainability as a waste collection system. This assessment is part of a broader exploration into waste management strategies, which have been subject to various studies evaluating their environmental impact and efficiency. For instance, Mora et al. (2014) conducted a Life Cycle Analysis (LCA) to assess the environmental implications of different waste management methods, including street-side containers, subterranean containers, doorstep collection, and pneumatic collection systems. Conversely, Gilardino et al. (2017), integrated operational research methods and LCA to devise an efficient collection-route system for garbage compactor trucks, aiming to reduce environmental impacts in Lima. Pérez et al. (2017) outlined a methodology for assessing the environmental impact of urban containerization systems using LCA, while Pires et al. (2017) examined the economic aspects alongside the environmental impact of curbside and exclusive bring systems. Social perspectives on common collection systems were also considered (Yildiz-Geyhan et al., 2017). Introduction of new technologies facilitated comparisons between conventional and novel systems such as vacuum collection.

Teerioja et al. (2012) compared a stationary pneumatic waste collection system with a traditional vehicle-operated door-to-door collection system in a densely populated urban area, focusing on economic aspects. Punkkinen et al. (2012) and Aranda-Usón et al. (2013) utilized LCA to evaluate the environmental sustainability of both collection methods. Iriarte et al. (2009) employed LCA to quantify and compare the potential environmental impacts of three selective collection systems: mobile pneumatic, multi-container, and door-to-door. Previous findings suggest that pneumatic systems tend to generate more air emissions due to electricity consumption and installation materials. However, when loads approach full capacity, the vacuum system exhibits superior environmental performance compared to conventional methods. Additionally, from an economic standpoint, pneumatic collection is estimated to be six times costlier than traditional systems (Teerioja et al., 2012).

As observed, studies conducted thus far have primarily focused on comparing pneumatic or door-to-door urban garbage collection systems (Iriarte et al., 2009; Laso et al., 2019; Baltrocchi APD., 2024; Dotsenko et al., 2022), predominantly using traditional traction vehicles rather than electric or green energy vehicles (Canals Casals et al., 2016; Canals Casals et al., 2017; Aryan et al., 2023) but according to Laso et al. (2019), pneumatic collection could be an environmentally friendly option for MSW management under a circular economy approach in urban centers, taking into account waste as an opportunity for a material or energy source. If the proposed waste collection robot functions as an electric vehicle, particularly one designated for door-to-door collection, as demonstrated by Yang et al. (2022), it is reasonable to anticipate a substantial reduction in emissions. This shift would make it a more viable option for waste management.

When assessing the collection systems from an economic perspective, Laso et al. (2019) and Yang et al. (2022) underscore the cost-effectiveness of the door-to-door system. However, a comprehensive comparison must be made between the initial installation costs and potential maintenance requirements of the complex mechanisms involved in pneumatic systems and the robots' operational

TABLE 3: Protocol for the Introduction of Robots.

Project Definition	Initial Studies	Technological Development of the Robot	Prototype Implementation
• Public Space • Stakeholders (Human Robot Interaction Roles: robot supervisor, robot operator, peer teammate, peer enduser, bystander, robotic urban set designer, researchers) • Need or Activity to be Developed by the Robot	• Studies on robot typology • Studies on public space • Study of interactions between "City" and "Robot" • Study and analysis of regulations and applicable legislation in the project, as well as the necessary licenses for it.	• Design and implementation of the robot • Testing of it in the laboratory **Design of the public space that will host the robot** • Implementation of the zones • Design of the communication equipment necessary for orientation/communication with the robot • Design of specific recharging/ repair spaces for the robot in the city • Design of the pick-up and delivery areas.	• Analysis of proper integration • User Acceptance Analysis (surveys/interviews/real experiences with prototypes) • Analysis of suitable schedules and spaces • Implementation in a controlled environment • Implementation in the city, controlled part. • Implementation in a real environment.

expenses, maintenance requirements, and long-term sustainability.

Shifting focus to the framework for implementing a last-mile robotic system in urban areas, Table 3 outlines the procedure used in this research for integrating a robot into public spaces.

The Table 3 show the protocol to develop and introdius a new tecnology in the city. This protocol is divided into four sections. The first section outlines the project's definition, including technical requirements, identification of interacting actors, and specific locations for deployment. The second section delves into an in-depth study of various robot typologies to determine the most suitable option. Additionally, this section examines the city and its characteristics, along with relevant project regulations.

The third section focuses on the technical development of the robot, design considerations for the public spaces it will interact with, communication systems, parcel delivery mechanisms, and other related aspects. Finally, the last section encompasses the realization of the prototype and its interaction with the environment. This stage involves analyzing citizen acceptance of the robot, making necessary adjustments for adaptation, and addressing any identified issues.

As previously mentioned, surveys were conducted with users prior to introducing the prototype into the urban environment, followed by personalized interviews after conducting robot implementation tests in the city. The vehicle utilized for these tests was the ONA(Human-Robot Interaction (HRI) Operational Navigation Autonomous), as described by Puig-Pey et al. (2023). ONA is an electric vehicle with approximately 8 hours of autonomy and dimensions similar to those of the proposed waste collection robot.

As seen in Table 3, it is essential to be in a connected city to implement robotic systems, as the device must communicate at all times to follow the predefined route without conflicts.

In analyzing the city, it is necessary to distinguish between different urban areas. In this study, we chose to classify the city into three parts: urban center, industrial zone, and neighborhoods/developments due to their different urban characteristics.

Simultaneously, we analyzed various types of robots currently available that could fit the activity we were developing. At this point, we opted to design a waste collection robot for developments and used ONA for the test, as seen earlier.

In the interviews as we could see, conducted during the implementation tests, we found that bystanders indicated, on a scale of 1 to 7, that 90% (taking into account ratings of 5, 6, and 7) would accept the presence of a robot in the public space (Figure 2). The scale from 1 to 7 indicates the degree to which the robot is accepted in the urban space. Where 1 is unfavorable and 7 is feasible).

They emphasize that the most feasible implementation they see at present would be in residential areas or industrial zones (university campuses, industrial estates, pedestrian urban centers, or small urban developments). They point out that it would be advisable to segregate urban spaces and that nighttime mobility would be the most suitable to minimize interference with bystanders. Therefore, we believe that the proposed activity is appropriate based on the suggestions of passersby.

The dimensions of the ONA were deemed suitable, suggesting that our waste collection robot would encounter no issues in this regard.

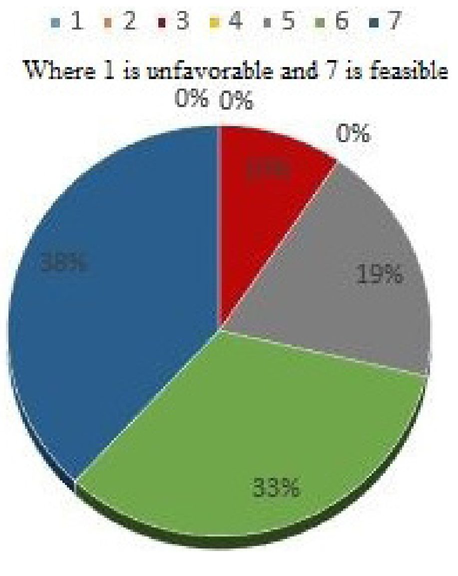

FIGURE 2: To what extent would you accept the presence of a robot in the current urban public space?

FIGURE 3: Year distribution of the number of publications on waste-collecting robots.

Regarding the city's preparedness for robot integration, participants expressed the need for significant investment. While acknowledging the potential reduction in unpleasant nighttime noise, concerns were raised about potential job displacement as a significant drawback to implementation.

Based on all these conclusions, also based on previous studies of waste disposal robots (Sushma et al., 2021; Gupta et al., 2022; Chen et al., 2023) and the type of robots at IRI (Institute of Robotics and Industrial Informatics) (ONA robot, (Puig-Pey et al., 2023)) and with the help of students from the Master's program in Industrial Electronics and Automation Engineering at the ESEIAAT (The School of Industrial, Aerospace and Audiovisual Engineering of Terrassa from Universitat Politècnica de Catalunya-BARCELONATECH), a waste-collecting robot design proposal has been developed, which can be seen in Figure 3.

This robot is designed to operate in the residential neighborhoods of Esplugues de Llobregat, where door-to-door waste collection is currently implemented with a different type of waste collected each day. The robot is equipped with caterpillar-like tracks, allowing it to navigate various surfaces with ease. The specifications of both the robot and the container are detailed in Table 4.

As the design of the robot and the different software and hardware components is not yet available, an information search has been carried out to determine the key factors for the design. Specification sheets are prepared based on the factors to be considered for a more sustainable design. A survey of 33 leading robotics companies was

TABLE 4: The technical specifications of the robot and the container.

Robot specifications		Container specifications	
Speed(m/s)	4	Speed(m/s)	4
Mass (Kg)	50	Mass(Kg)	150
Speed-up(m/s^2)	1.6	Speed-up(m/s^2)	1.6
Power(W)	320	Power (W)	960
Torque (Nm)	40	Torque (Nm)	120

conducted, as used in Zerkane et al. (2015). Some of the key factors identified include energy saving, durability optimization, recyclability, biodegradability, renewability, and reusability. However, there is still a lot of work to be done in this area.

As shown in Tables 3 and 4 and Figure 3, the preliminary design indicates that each container will have a capacity of 500 liters, and it is estimated that there will be one robot for every 300 households or more (considering that the average garbage production per family per day is 1.5 kg), forming a network of robots in more populated environments. The system is electric, equipped with lithium batteries, and rechargeable through solar panels located on the top of the container, if conditions permit. The current robot can receive instructions from an operator, follow a programmed route, includes both manual and automatic emergency stops, and is equipped with a trash compactor (Dalmasso et al., 2023).

It is clear that the production and disposal of batteries significantly contribute to the overall environmental footprint of BEVs (Koroma et al. 2022). However, as demonstrated in the work by Yang et al. (2022), compared to combustion engines, the environmental impact is lower, although it is clearly influenced by the energy mix of the country where the BEV or robot is implemented.

Therefore, as a final reflection we could say that the integration of robots into urban spaces presents a myriad of advantages and disadvantages (Table 5 presents a first analysis of them). On one hand, robots can streamline various urban processes, such as waste management, transportation, and infrastructure maintenance, leading to increased efficiency and reduced operational costs.

Additionally, robots can mitigate risks to human workers by performing tasks in hazardous or challenging environments. However, their introduction may also raise concerns regarding job displacement and social acceptance. Moreover, the complexity and cost associated with implementing and maintaining robotic systems in urban environments pose significant challenges. Therefore, while robots hold promise for enhancing urban life, careful considera-

TABLE 5: Advantages and disadvantages of integrating robots into urban spaces.

Aspect	Advantages	Disadvantages
Technological	• Automation of repetitive tasks. • Increased precision and efficiency in waste collection. • Integration of advanced technologies.	• Vulnerability to technical failures and cyberattacks. • High initial and ongoing costs associated with development and maintenance. • The delayed implementation of technology in connected cities poses challenges for current robot navigation.
Social	• Improvement of working conditions. • Potential for creating new jobs. • Reduction of pollution and noise.	• Concerns over job loss. • Challenges of acceptance and adaptation by the population.
Environmental	• Reduction of greenhouse gas emissions. • Improvement in waste management and collection efficiency.	• Environmental impact of production and disposal of electronic components. • Energy consumption during manufacturing and operation.
Economic	• Long-term reduction in operational costs. • Savings generation through efficient resource management.	• High initial costs. • Uncertainty about return on investment and long-term economic viability.

tion of both their benefits and drawbacks is essential for successful integration into urban spaces.

4. CONCLUSIONS

As we have analyzed, in reviewing the collection of studies (Table 2), the critical role of digitalization, artificial intelligence, and other advanced technologies in waste management emerges prominently. These technologies are pivotal in developing more efficient waste-collecting robots. Many papers as we saw, underscore the circular economy as a central approach to waste management, highlighting how waste-collecting robots can facilitate the transition to this model. Additionally, the importance of environmental sustainability in waste management and the creation of environmentally friendly technologies and robots is emphasized.

Waste-collecting robots, as noted by Chen et al. (2023), are viewed as efficient, automated tools for waste collection and sorting. They can significantly enhance efficiency and reduce the costs associated with waste management. However, challenges such as autonomous navigation in complex urban environments, safe interaction with citizens, and the coordination of multiple tasks simultaneously present significant obstacles yet.

Parallel to the information search for the waste collection robots, a deployment new protocol for these robots in public spaces has been developed. As we have seen, this includes phases to address interaction with public spaces, people, and existing mobility systems.

Environmental sustainability assessments, such as those conducted by Mora et al. (2014), Gilardino et al. (2017), Pérez et al. (2017), and Pires et al. (2017), provide insights into the environmental implications of waste management methods. These studies, employing Life Cycle Analysis (LCA), reveal that while pneumatic systems may generate more air emissions due to electricity consumption, they exhibit superior environmental performance when operating at full capacity. Economic evaluations, such as those by Teerioja et al. (2012), suggest that pneumatic collection systems are significantly more costly than traditional methods. Robotic systems could balance cost and emissions, but comprehensive studies are still needed. The key factors necessary for the design of robots have been analysed, based on the survey developed by Zerkane et al. (2015), of 33 leading companies in the development of robots.

Studies primarily comparing pneumatic and door-to-door collection systems (Baltrocchi APD., 2024; Dotsenko et al., 2022) typically use traditional traction vehicles rather than electric or green energy vehicles (Canals Casals et al., 2016, 2017). Transitioning to electric vehicles for waste collection, particularly for door-to-door systems, is likely to result in substantial emission reductions, making it a more viable waste management option.

The economic perspective, as discussed by Laso et al. (2019) and Yang et al. (2022), highlights the cost-effectiveness of the door-to-door system. However, a comprehensive evaluation of the economic advantages of integrating robotic systems compared to pneumatic facilities requires a more in-depth analysis. Factors such as initial setup costs, operational expenses, maintenance requirements, and long-term sustainability must be thoroughly examined.

In implementing last-mile robotic systems within urban areas, it is essential to follow a structured protocol as we have presented. This includes defining the project, studying various robot typologies, focusing on the technical development of the robot, and analyzing citizen acceptance and necessary adjustments for adaptation.

In conclusion, integrating robots into urban spaces offers numerous advantages, including increased efficiency and reduced operational costs. However, challenges such as potential job displacement, social acceptance, and the complexity and cost of implementation must be addressed. Careful consideration of these factors is crucial for the successful integration of robots into urban environments, especially based on data obtained from pedestrians who would share public space with robots.

The consideration of environmental, social, economic and efficiency factors is crucial for the successful integration of robots in urban environments, as we present in the protocol and it is necessary to obtain some of these from pedestrians who would share public space with robots.

In future work, we will conduct a technical comparison with systems proposed by other institutions. Furthermore, we will perform environmental and social analyses to evaluate the device's integration and incorporate diverse proposals from stakeholders.

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REFERENCES

Ada, E., Ilter, H. K., & Kazancoglu, Y. (2023). Smart technologies for collection and classification of electronic waste. International Journal of Quality & Reliability Management. Vol 8, 10 January 2023, https://doi-org.recursos.biblioteca.upc.edu/10.1108/IJQRM-08-2022-0259

Ahmad, S., Imran, & Kim, D. (2020). Optimal Route Recommendation for Waste Carrier Vehicles for Efficient Waste Collection: A Step Forward Towards Sustainable Cities. IEEE Access. Volume: 8, page: 77875 – 77887. http://dx.doi.org/10.1109/ACCESS.2020.2988173

Aljohani K. and Thompson, R. G. (2019). A Stakeholder-Based Evaluation of the Most Suitable and Sustainable Delivery Fleetfor Freight Consolidation Policies in the InnerCity Area. Sustainability, vol. 11, n.o 1, Art. n.o 1, ene. 2019, http://dx.doi.org/10.3390/su11010124.

Aranda-Usón, A.; Ferreira, G.; Zambrana-Vázquez, D.; Zabalza-Bribián, I.; Llera-Sastresa, E. (2013). Environmental-benefit analysis of two urban waste collection systems. Science of The Total Environment. 463–464,72–77. https://doi.org/10.1016/j.scitotenv.2013.05.053

Aryan Y., Kumar A,. Subham, Ranjan S. (2023). Environmental and economic assessment of waste collection and transportation using LCA: A case study. Environmental Research 231 (2023) 116108. https://doi.org/10.1016/j.envres.2023.116108

Azza E I., Rasha S., Mona M., Heba A., Young I., Mohamed S., (2023). International Journal of Advanced Computer Science and Applications. Vol. 14, No. 6, http://dx.doi.org/10.14569/IJACSA.2023.0140697 .

Badve M., Chaudhari A., Davda P., Bagaria V., Kalbande D. (2024). Garbage Collection System using IoT for Smart City. Proceedings of the Fourth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC). pp. 138-143, https://doi.org/10.1109/I-SMAC49090.2020.9243387.

Baltrocchi, A.P.D.; Maggi, L.; Carnevale Miino, M.; Torretta, V.; Rada, E.C. Comparison of Mixed and Door-to-Door Systems for Urban Waste Collection in Terms of Effectiveness and Greenhouse Gas Emissions: A Case Study from Two Mountainous Italian Valleys. Resources 2024, 13, 17. https://doi.org/10.3390/resources13010017

Bassi S., Christensen T., Damgaard A., (2017). Environmental performance of household waste management in Europe - An example of 7 countries. Waste Management. Volume 69, November 2017, Pages 545-557. https://doi.org/10.1016/j.wasman.2017.07.042.

Bharanikumar R., Maheswari K T., Bharath M., Sangeethkumar C., (2022). Design and Simulation of Object Detection Based Autonomous Trash Collector Bot. Smart Technologies, Communication & Robotics. Pp. 1-5, https://doi.org/10.1109/STCR55312.2022.10009636.

Borrmann, D., Nuchter, A., & Velagic, J. (2014). A mobile robot based system for fully automated thermal 3D mapping. Advanced Engineering Informatics. Volume 28, Issue 4, October 2014, Pages 425-440 https://doi.org/10.1016/j.aei.2014.06.002

Boysen, N. Fedtke, S. and Schwerdfeger, S. (2021). Last-mile delivery concepts: a survey from an operational research perspective, OR Spectrum, vol. 43, n.o 1, pp. 1-58, mar. http://dx.doi.org/10.1007/s00291-020-00607-8.

Brunner, P. H., Morf L.S. (2024). Waste to energy, indispensable cornerstone for circular economy: A mini-review. Waste Management & Research, pp 1–13. https://doi.org/10.1177/0734242X241227376

Burde, H; Rajput, S; Kajaria, H; Choudhari, V; Verma, A; Prashar, M; Vijayalakshmi, S. (2023). Development of an autonomous disinfection robot capable of last mile delivery. Research article. Volume 2690, Issue 1, 24 March 2023 https://doi.org/10.1063/5.0122264

Canals Casals, Ll., Martinez-Laserna, E., Amante García, B., Nieto, N. (2016). Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. Journal of Cleaner Production 127 , 425e437. http://dx.doi.org/10.1016/j.jclepro.2016.03.120 .

Canals Casals, Ll., Amante García, B., Aguesse, F., Iturrondobeitia, A. (2017). Second life of electric vehicle batteries: relation between materials degradation and environmental impact. Assessing and managing life cycles of electric vehicles. Volume 22, pages 82–93, http://dx.doi.org/10.1007/s11367-015-0918-3.

Chang, B. R., Tsai, H. F., & Yin, T. K. (2019). Smart Trash Can Robot System with Integration of Internet of Things and Mobile Applications. Sensors and Materials. Vol 31, pp. 3495-3516, https://doi.org/10.18494/SAM.2019.2563

Chen, L. B., Huang, X. R., Chen, W. H., Pai, W. Y., Huang, G. Z., & Wang, W.C., (2023). Design and implementation of an artificial intelligence of things-based autonomous mobile robot system for cleaning garbage. IEEE Sensors Journal. Volume: 23 Issue: 8, https://doi.org/10.1109/JSEN.2023.3254902

Clark, B. (2020). The impacts of autonomous vehicles on local government budgeting and finance: case of solid waste collection. National Tax Journal. https://doi.org/10.17310/ntj.2020.1.08

Dalmasso M., Domínguez-Vidal JE., Torres-Rodríguez I., Jiménez P., Garrell A., Sanfeliu A., (2023). Shared Task Representation for Human–Robot Collaborative Navigation: The Collaborative Search Case. International Journal of Social Robotics. Volume 16, pages 145–171, https://doi.org/10.1007/s12369-023-01067-0 .

D'Amico, G., Arbolino, R., & Ioppolo, G. (2022). Digitalisation driven urban metabolism circularity: A review and analysis of circular city initiatives. Land Use Policy. Volume 112, January 2022, 105819 https://doi.org/10.1016/j.landusepol.2021.105819

Delice E. Adar T., Emeç S. Akkaya G. (2019). A Comprehensive Analysis of Location Selection Problem for Underground Waste Containers Using Integrated MC-HFLTS&MAIRCA and MABAC Methods. European Journal of Science and Technology Special Issue, pp. 15-33, October. https://doi.org/10.31590/ejosat.594713.

Deloitte Spain (2023). Logística de Última Milla, Deloitte España. https://www2.de- loitte.com/es/es/pages/operations/articles/logistica-de-ultima-milla.html.

Demir, E. Syntetos, A. and Van Woensel, T. (2022). Last mile logistics: Research trends and needs. IMA Journal of Management Mathematics, vol. 33, n.o 4, pp. 549-561, http://dx.doi.org/10.1093/imaman/dpac006.

Di Maria, F., Sisani, F., El-Hoz, M., Mersky. RL, (2020). How collection efficiency and legal constraints on digestate management can affect the effectiveness of anaerobic digestion of bio-waste: An analysis of the Italian context in a life cycle perspective. Science of The Total Environment. Volume 726, 15 July 2020, 138555. http://dx.doi.org/10.1016/j.scitotenv.2020.138555

Dotsenki A.I.; Kustarev G.V., Andryukhov N.M., (2022). 2022 Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED) | 979-8-3503-9770-3/22/$31.00 2022 IEEE pp. 1-4 https://doi.org/10.1109/TIRVED56496.2022.9965556.

Espinosa-Aquino, B., Durany, X. G., & Vargas, R. Q. (2023). The Role of Informal Waste Management in Urban Metabolism: A Review of Eight Latin American Countries. Sustainability. 15(3), 1826 https://doi.org/10.3390/su15031826

Faniran, V, Badru, A, Ajayi, N (2017) Adoptin Scrum as an Agile Approach in Distributed Sftware Development: A Review of Literature. 1st International Conference on Next Generation Computing Applications. pp. 36-40 http://dx.doi.org/10.1109/NEXTCOMP.2017.8016173

Fang, B. B., Yu, J. C., & Yap, P. S. (2023). Artificial intelligence for waste management in smart cities: a review. Environmental Chemistry Letters. Vol 21, pp 1959–1989, http://dx.doi.org/10.1007/s10311-023-01604-3

Fischer Cl., Steiner M., Neuhold M., Papa M., Markis A., Schlund S., (2022). An Investigation of the Measurement of Transient Contacts in Human-Robot Interaction. Advances in Service and Industrial Robotics. RAAD 2022. Mechanisms and Machine Science, vol 120. https://doi-org.recursos.biblioteca.upc.edu/10.1007/978-3-031-04870-8_64

Gilardino, A.; Rojas, J.; Mattos, H.; Larrea-Gallegos, G.; Vázquez-Rowe, I. (2017). Combining operational research and Life Cycle Assessment to optimize municipal solid waste collection in a district in Lima (Peru). Journal of Cleaner Production, Vol156, pp 589–603. https://doi.org/10.1016/j.jclepro.2017.04.005 .

Guimaraes, B., Simoes, P., & Marques, R. C. (2010). Does performance evaluation help public managers? A Balanced Scorecard approach in urban waste services. Journal of Environmental Management. Vol 91, pp 2632-2638. http://dx.doi.org/10.1016/j.jenvman.2010.07.039.

Gupta A., Joop van der Schoor M., Bräutigam J., Bladinieres V., Fritz T., Göhlich D. 2022. IEEE Robotics and Automation Letters, VOL. 7, NO. 4, October. https://doi.org/10.1109/LRA.2022.3188900 .
Han, Z. Y., Ye, C. W., & Shi, G. Z. (2019). Characteristics and management modes of domestic waste in rural areas of developing countries: a case study of China. Environmental Science and Pollution Research. Vol 26, pp 8485–8501. http://dx.doi.org/10.1007/s11356-019-04289-w
Han, Z. Y., Zeng, D., & Mou, Z. S. (N.D). Public willingness to pay and participate in domestic waste management in rural areas of China. Resources Conservation and Recycling. Volume 140, pp 166-174 https://doi.org/10.1016/j.resconrec.2018.09.018
Huang, R., Li, H., Suomi, R., Li, C., & Peltoniemi, T. (2023). Intelligent Physical Robots in Health Care: Systematic Literature Review. Journal of Medical Internet Research, 25(6), e3452. http://dx.doi.org/10.2196/39786
Hwang, J., Kim, J. J., Choe, J. Y. J., & Kim, H. M. (2023). The importance of information quality according to the type of employee in the airline industry: Robot versus human. International Journal of Hospitality Management, 42, 123-135. http://dx.doi.org/10.1016/j.ijhm.2023.103537
Hwang, J., Lee K., Kwon D.,(2007) A Formal Method of Measuring Interactivity in HRI. 16th IEEE International Conference on Robot & Human Interactive Communication .August 26 - 29, 2007 / Jeju, Korea. http://dx.doi.org/10.1109/ROMAN.2007.4415183.
Hyeong Suk Na, Sang JinKweon, y Kijung Park, (2021). Characterization and design for last mile logistics: are view of the state of the art and future directions, AppliedSciences,vol.12,n.o 1, p. 118 (21 pp.), http://dx.doi.org/10.3390/app12010118.
Iriarte, A.; Gabarrell, X.; Rieradevall, J. (2009). LCA of selective waste collection systems in dense urban areas. Waste Management. Vol 29, Issue 2, pp 903-914. https://doi.org/10.1016/j.wasman.2008.06.002.
Koroma M., Costa D., Philippot M., Cardellini G., Hosen Md. Coosemans., Messagie M. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. Science of the Total Environment. Vol:831, pp:154859. http://dx.doi.org/10.1016/j.scitotenv.2022.154859.
Laso,J., García-Herrero, I., Margallo, M., Bala, A., Fullana-i-Palmer. P., Irabien, A., Aldaco, R. (2019). LCA-Based Comparison of Two Organic Fraction Municipal Solid Waste Collection Systems in Historical Centres in Spain. Energies. Vol:12, pp1407; http://dx.doi.org/10.3390/en12071407.
Liang-Bi Chen, Xiang-Rui Huang, Wei-Han Chen, Wen-Yu Pai, Guan-Zhi Huang, and Wei-Chien Wang (2023).Design and Implementation of an Artificial Intelligence of Things-Based Autonomous Mobile Robot System for Cleaning Garbage. IEEE SENSORS JOURNAL, VOL. 23, NO. 8, 15 APRIL 2023. https://ieeexplore-ieee-org.recursos.biblioteca.upc.edu/stamp/stamp.jsp?tp=&arnumber=10070582
Maletz, R., Wohmann, S., Pukhnyuk, A., (2018). Comparison of waste management systems in western and transition economies within the watra project. Detritus. Vol 02 , pp 96-104. https://doi.org/10.31025/2611-4135/2018.13659 .
Moanaro, A., Nzanthung, N. (2024). Overview of municipal solid waste management in sub-tropical climatic region of North Eastern India. Environmental Science and Pollution Research. Vol 31, pp 23307–23321. https://doi.org/10.1007/s11356-024-32689-0 .
Molinillo, S., Rejón-Guardia, F., & Anaya-Sánchez, R. (2023). Exploring the antecedents of customers' willingness to use service robots in restaurants. Service Business, 42(2), 123-135. https://doi.org/10.1007/s11628-022-00509-5
Mora, C.; Manzini, R.; Gamberi, M.; Cascini, A. (2014). Environmental and economic assessment for the optimal configuration of a sustainable solid waste collection system: A "kerbside" case study. Prod. Plan. Control 2014, 25, 737–761. http://dx.doi.org/10.1080/09537287.2012.750386
Morakabatchian M., Almodaressi SA., Barzegar M R., Mokhtari M., (2021). Optimization of Waste Collection System Using Underground Containers with Source Separation Plan (Case Study: District 3 of Yazd Municipality, Iran). J Environ Health Sustain Dev. 2(4):422-31. https://www.academia.edu/79072332/Optimization_of_Waste_Collection_System_Using_Underground_Containers_with_Source_Separation_Plan_Case_Study_District_3_of_Yazd_Municipality_Iran_
Muntasir Shovon, S., Ahamed Akash, F., Rahman, W., Rahman, A., Chakraborty, P., Zakir Hossain, H.M., Uddin Monir, M. (2024). Strategies of managing solid waste and energy recovery for a developing country – A review. Heliyon. Vol10, pp24736. https://doi.org/10.1016/j.heliyon.2024.e24736
Ortenzi, V., Stolkin, R., & Mistry, M. (2017). Hybrid motion/force control: a review. Advanced Robotics. Vol31, pp 1102-1113. https://doi.org/10.1080/01691864.2017.1364168
Park, SJ; Ahn, S; Shin , JP; Kim, H; Yang, J; Kim,YH; Lim, K; and Seo, TW. (2023). WAVE: Last mile delivery robotic platform with stair-climbing ability via four-bar linkage-based locomotion. IEEE/ASME Transactions on Mechatronics. Vol. 29, pp. 313-323. https://doi.org/10.1109/TMECH.2023.3275919
Pérez, J.; Lumbreras, J.; de la Paz, D.; Rodríguez, E. (2017). Methodology to evaluate the environmental impact to urban solid waste containerization system: A case study. Journal of Cleaner Production. Vol 150, pp 197-213. https://doi.org/10.1016/j.jclepro.2017.03.003.
Pires, A.; Sargedas, J.; Miguel, M.; Pina, J.; Martinho, G. (2017). A case study of packaging waste collection systems in Portugal–Part II: Environmental and economic analysis. Waste Management. Vol 61, pp 108-116. https://doi.org/10.1016/j.wasman.2016.11.032 .
Puig-Pey , A., Zamora , J.Ll., Amante, B., Moreno, J., Garrell, A., Grau, A., Bolea, Y., Sanfeliu, A., Human acceptance in the Humen-Robot Interaction scenario for last-mile godos delivery. IEEE Conference on Advanced Robotics and its Social Impact (ARSO). Pp. 33-39. http://dx.doi.org/10.1109/ARSO56563.2023.10187432
Punkkinen, H.; Merta, E.; Teerioja, N.; Moliis, K.; Kuvaja, E. (2012). Environmental sustainability comparison of a hypothetical pneumatic waste collection system. Waste Management. 32, 1775–1781. https://doi.org/10.1016/j.wasman.2012.05.003.
Qing Song Zhang. Environment Pollution Analysis on Smart Cities Using Wireless Sensor Networks. River Publishers Journals . 2022-12-28. 2023: Vol 42 Iss 1. https://doi.org/10.13052/spee1048-5236.42112
Raihan N., Rahman M., Alam F., Syed E.,(2020) . A Novel Approach for Waste Collection: Automated Waste Collecting Robot with Advanced Image Recognition Technology and Onboard Robotic Arm. 2020 IEEE Region 10 Symposium (TENSYMP) 5-7 June 2020, Dhaka, Bangladesh. https://doi.org/10.1109/TENSYMP50017.2020.9230888 .
Ranieri, L. Digiesi, S. Silvestri, B. and Roccotelli. M. (2018). A Review of Last Mile Logistics Innovations in an Externalities Cost Reduction Vision, Sustainability, vol. 10, https://doi.org/10.3390/su10030782.
Rossit,D. G., Nesmachnow, S., (2022).Waste bins location problem: A review of recent advances in the storage stage of the Municipal Solid Waste reverse logistic chain. Journal of Cleaner Production 342 (2022) 130793. https://doi.org/10.1016/j.jclepro.2022.130793
Saragih, Y., Hidayat, R., & Hadikusuma, R. S. , (2023). Community perspective on the waste management system in Lambangsari Bekasi Village based on smart garbage robots. Jurnal Ilmiah. Vol 382, pp135296, https://doi.org/10.1016/j.jclepro.2022.135296
Sarc, R., Curtis, A., & Pomberger, R. (2019), Digitalisation and intelligent robotics in value chain of circular economy oriented waste management – A review. Waste Management Vol 95, pp 476-492. https://doi.org/10.1016/j.wasman.2019.06.035
Satav, A. G., Kubade, S., & Pawar, A. (2023). A state-of-the-art review on robotics in waste sorting: scope and challenges. International Journal of Interactive Design and Manufacturing - IJIDEM. Vol 17, pp 2789–2806. https://doi.org/10.1007/s12008-023-01320-w
Shaklab, E; Karapetyan, A; Sharma, A ; Mebrahtu, M; Basri, M ; Nagy, M ; Khonji, M; and Dias, J. (2023) . Towards Autonomous and Safe Last-mile Deliveries with AI-augmented Self-driving Delivery Robots. Computer Science. Vol 1. https://doi.org/10.48550/arXiv.2305.17705
Soori, M., Arezoo, B., & Dastres, R. (2023). Artificial intelligence, machine learning and deep learning in advanced robotics: A review. Cognitive Robotics, 1(1), 45-60. https://doi.org/10.1016/j.cogr.2023.04.001
Sunil M. and Shanavas M. (2023). A Perspective of Autonomous Office Trash Collector Robot: The Research and
Development in Field Robotics. Advances in Business Informatics empowered by AI & Intelligent Systems. Book https://dx.doi.org/10.46679/978819573220309

Sushma S C., Medhasvi K., Princy R., (2021). Garbage Detection and Path-Planning in Autonomous Robots. 9th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO) Amity University, Noida, India. Sep 3-4. https://doi.org/10.1109/ICRITO51393.2021.9596382

Teerioja, N.; Moliis, K.; Kuvaja, E.; Ollikainen, M.; Punkkinen, H.; Merta, E. (2012). Pneumatic vs. door-to-door waste collection systems in existing urban areas: A comparison of economic performance. Waste Management. 32, 1782–1791. https://doi.org/10.1016/j.wasman.2012.05.027 .

Tomitagawa, K. , Anuntachai A., Chotiphan S., Wongwirat O., Kuchii S. (2024). Adapted ACO Algorithm for Energy-Efficient Path Finding of Waste Collection Robot. 2022 The 22nd International Conference on Control, Automation and Systems (ICCAS 2022) BEXCO, Busan, Korea, Nov. 27~Dec. 01, 2022. https://doi.org/10.23919/ICCAS55662.2022.10003892.

Tonni Agustiono Kurniawan, Christia Meidiana, Mohd Hafiz Dzarfan Othman, Hui Hwang Goh, Kit Wayne Chew. (2023) Strengthening waste recycling industry in Malang (Indonesia): Lessons from waste management in the era of Industry 4.0. Journal of Cleaner Production. Vol 382. https://doi.org/10.1016/j.jclepro.2022.135296

Tuli T B., Manns M., Zeller S., (2022). Human motion quality and accuracy measuringmethod for human–robot physical interactions. Intelligent Service Robotics Vol15:503–512. https://doi.org/10.1007/s11370-022-00432-8

Yamaji, Y., T., & Okada, M. (2011). Stb: Child-dependent Sociable Trash Box. International Journal of Social Robotics. Vol 3, pp 359–370. https://doi.org/10.1007/s12369-011-0114-y

Yang, N.; Li, F.; Liu, Y.; Dai, T.;Wang, Q.; Zhang, J.; Dai, Z.; Yu, B. (2022) Environmental and Economic Life-Cycle Assessments of Household FoodWaste Management Systems: A Comparative Review of Methodology and Research Progress. Sustainability 2022, 14, 7533. https://doi.org/10.3390/su14137533.

Yildiz-Geyhan, E.; Altun-Ciftçioglu, G.A.; Neset Kadirgan, M.A. (2017). Social life cycle assessment of different packaging waste collection system. Resources, Conservation and Recycling. 124, 1–12. https://doi.org/10.1016/j.resconrec.2017.04.003

Zerkane SE., Vareille J., Autret Y. Parc P., (2015). LCA in robotics, new challenges for the future. 2014 [avniR] Conference, Life Cycle in Practice, Nov 2014, Lille, France.2014. htto://hal.univ-brest.fr/hal-01109735.