Ontology-based Intelligent Urban Waste Management System

Muhammad Mehran
Computer Science
Ulster University *(Birmingham Campus)*
Birmingham, UK
mehran-m@ulster.ac.uk

***Abstract*—Urban waste management is becoming more complicated, necessitating more sustainable and intelligent solutions. An ontology-based Intelligent Urban Waste Management System which uses semantic information to enhance garbage collection, disposal, recycling is presented in this study. Bins, facilities, different sorts of waste, and locations for the best placement of bins and facilities are important ideas. Vehicles are connected to activities like garbage pickup and processing, and routes stand in for collecting routes. Route optimization, real-time monitoring, and targeted waste processing are made possible by relationships like *isLocatedIn*, *isCollectedBy*, and *isAssignedTo*. The system facilitates decisions such as locating facilities for particular waste kinds and recognizing bins that need to be collected right away using *SPARQL* queries. This framework reduces environmental impact, conserves resources, and streamlines processes by using semantic technologies.**

Keywords—Ontology, Urban Waste Management, Semantic Modeling, SmartBin, Recycling Facility, Waste Collection Vehicles, Route Optimization, SPARQL Queries, Intelligent Waste Systems.

I. Introduction

The growing development of cities worldwide has resulted in a huge rise in trash creation, providing significant issues for sustainable waste management. Traditional systems, depending on static schedules and manual interventions, usually experience inefficiencies such as overflowing bins, excessive fuel usage, and inadequate resource allocation. These challenges highlight the necessity for creative strategies that guarantee environmental sustainability and operational efficiency.

An ontology-based Intelligent Urban Waste Management System (UWMS) solves these difficulties by merging semantic technologies, the Internet of Things, and Artificial Intelligence. Ontologies give a systematic representation of domain knowledge, aiding reasoning, automation, and informed decision-making [1]. By integrating real-time data from IoT-enabled smart bins and sensors, paired with powerful route optimization algorithms, the system can dynamically adjusts to complicated waste management scenarios, enabling effective collection, segregation, and processing of urban garbage [5].

II. Problem Description

Urban regions have substantial difficulties in garbage management, leading to ecological damage and economic detriment. A significant concern is the overflow of garbage containers, as static collection schedules do not align with actual waste accumulation, resulting in unclean circumstances. Moreover, trucks following predetermined routes frequently waste resources, including fuel and time, by servicing bins that are not at capacity. A further difficulty is the inadequate segregation of garbage, which obstructs efficient recycling and processing, hence exacerbating dependence on landfills. The irregular monitoring of trash levels and conditions, usually conducted manually, contributes to inefficiency through frequent mistakes and delays. Moreover, these inefficient systems intensify environmental issues by increasing greenhouse gas emissions, deteriorating air quality, and depleting energy supplies.

III. Justification About Ontology in Knowledge Representation and Reasoning

Ontology plays a crucial role in the Intelligent Urban Waste Management System (UWMS) by providing a structured and semantic foundation for knowledge representation and reasoning. In the terms of trash management, the complexity of interactions between waste kinds, bins, vehicles, routes, and facilities needs a systematic strategy to model, organize, and infer information. Ontology gives the following benefits:

A. Enhanced Knowledge Representation

Ontologies provide a common, reusable, and machine-understandable structure for describing domain knowledge. They utilize hierarchical organization, where categories like Waste, Bins, Vehicles, and Routes are arranged with subclasses, such as Recyclable Waste and Organic Waste, to capture domain-specific data. Additionally, connections and characteristics are carefully specified, such as *isLocatedIn*, which connects bins to areas, and *isProcessedAt*, which links garbage to facilities, assuring unambiguous and consistent representation. Ontologies also assist data integration by combining diverse data sources, like IoT sensor data from smart bins and GIS data for route mapping, into a coherent and complete framework [8].

B. Facilitating Automated Reasoning

Reasoning engines like Pellet and *HermiT* employ current data and axioms to infer new knowledge, allowing intelligent decision-making inside the system. These engines help categorization by automatically designating bins as "Overflow" when their *hasFillLevel* surpasses 80%. They also assist inference by finding appropriate disposal facilities for certain categories of garbage based on specified rules, such as diverting recyclable items to a recycling facility [7].

C. Evidence from Related Work

Several studies underline the efficacy of ontologies in urban trash management and related sectors. Research suggests that ontology-based smart waste management systems boost decision-making in garbage collection and segregation by combining IoT and AI technology [6][8]. These technologies increase operating efficiency and promote environmental goals through optimal resource usage. Ontologies have also been widely implemented in environmental management, for example Open Geospatial Consortium's Sensor Web Enablement framework, which integrates and reasons over sensor data, comparable to IoT-enabled smart bins in trash management [3]. In smart city applications, ontologies have proven effective for integrating IoT devices and enabling intelligent decision-making in areas like traffic management, energy optimization, and air quality monitoring, showcasing their adaptability and utility in addressing complex urban challenges [2][10].

IV. Prior Knowledge Required for Intelligent Urban Waste Management System

To develop, implement, and assess Intelligent Urban Waste Management System (UWMS), a good grasp of numerous disciplines is essential. The following knowledge domains are crucial for the proper creation and operation of such a system:

A. *Waste Management Processes*

Understanding waste management systems includes familiarity with the varieties of trash, including recyclable, organic, hazardous, and general categories. It also involves knowledge of garbage collecting methods, encompassing both old and modern approaches, along with recycling and disposal procedures to guarantee adequate segregation and compliance with environmental regulations.

B. *Urban Infrastructure Knowledge*

Knowledge of urban infrastructure involves the use of GIS data to map bin locations, routes, and facilities, as well as insights into residential, industrial, and commercial zones to manage varied trash generating patterns. Awareness of municipal operations is also required to link garbage collection with local authorities' obligations.

C. *Ontology and Semantic Web Concepts*

A thorough foundation in ontology foundations, including concepts, classes, properties, and taxonomies, is necessary. Proficiency with ontology languages like as *OWL*, *RDF*, and *SPARQL* is necessary, along with experience with reasoning engines like Pellet or *HermiT* to enable automated decision-making and knowledge inference.

D. *System Design and Development*

Expertise in creating scalable systems that combine IoT devices, ontology frameworks, and reasoning engines is crucial. Familiarity with interoperability standards and skill in programming languages like Python or Java are important for easy integration and customization.

E. *Sustainability and Policy Knowledge*

Comprehending the environmental impact of improper waste disposal and the advantages of sustainable methods like recycling and resource recovery is vital. Familiarity with waste management legislation ensures compliance and compatibility with sustainability goals.

V. Step-by-step Methodology and Implementation

The process for constructing the Intelligent Urban Waste Management System (UWMS) utilizing ontology-based knowledge representation and reasoning contains many important components. This solution provides effective waste collection, route optimization, and sustainable waste management practices using semantic technologies and real-time data integration. Below, I discuss the step-by-step technique along with a description of the concepts and relations produced in Protégé, an ontology editing tool.

A. *Defining the Domain and Identifying Key Concepts*

First stage in constructing the ontology for the UWMS is to identify and describe the important concepts that characterize the domain of urban waste management. These concepts were constructed in Protégé, a strong ontology editor, into classes that include the major components of the system.

- *Bin*: Represents the rubbish containers used to collect waste. Subclasses include *SmartBin* and *StandardBin*.
- *Facility*: Represents recycling or disposal centres for different waste kinds.
- *Location*: Represents geographical data relating to urban trash management, such as the location of bins, facilities, and routes.
- *Route*: Refers to the predetermined or dynamic pathways followed by collecting vehicles.
- *Vehicle:* Refers to the garbage collecting trucks, including subclasses for certain categories, such as *GarbageTruck* and *RecyclingTruck*
- *Waste*: Represents all kinds of waste such as *RecyclableWaste*, *OrganicWaste*, *HazardousWaste*).

B. *Creating Concept Hierarchies*

In the following phase, I developed concept hierarchies to define subclass connections and better describe the domain. Each class was constructed based on its features, leading to the hierarchy depicted in Fig 1.

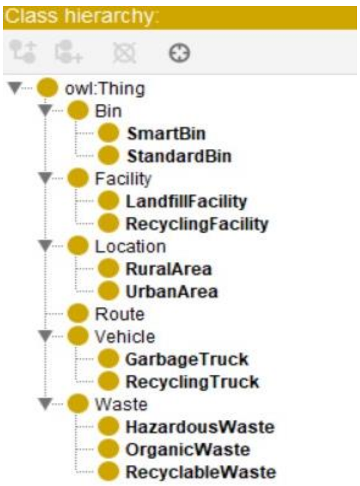

Fig 1. Concept Hierarchy

This hierarchy helps portray the domain in a clear, systematic fashion.

C. *Defining Relations (Properties) and Their Hierarchies*

Once the concepts were created, I continued to define the connections (properties) between these concepts. There are two sorts of properties utilized in the ontology: object properties and data properties.

a) Object Properties:

Object properties describe associations amidst two persons or instances of distinct classes. I developed various properties of objects to define the connections between concepts. Some of the object properties produced include:

Fig 2. Object Properties

- *isAssignedTo:* Associates vehicle with designated route.
- *isCollectedBy:* Associates bin with vehicle designated for its collection.
- *isLocatedIn:* Associates bin with a certain location or region.
- *isProcessedAt:* Associates garbage with a facility for processing (recycling or disposal).
- *hasBin:* Associates route with its corresponding bins.

These object attributes assist specify the relationship between multiple ideas, such as pairing a smart bin with its assigned collection truck.

b) Data Properties:

Data properties specify characteristics that offer more details about the instances of a class. These features are critical for recording Realtime data for example fill levels, time, and weight of garbage in bins. Some data attributes contained in the ontology are:

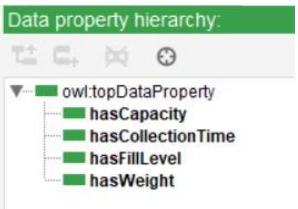

Fig 3. Data Properties

- *hasFillLevel:* Represents fill level of a bin, measured as a percentage (e.g., 80%).
- *hasWeight:* Represents weight of the waste in bin.
- *hasCapacity:* Defines maximum capacity of a bin.
- *hasCollectionTime:* Represents scheduled collection time of the bin.

These data attributes are vital for integrating real-time data from IoT-enabled devices, which allow for the dynamic monitoring and management of garbage collection.

c) Creating Instances (Individuals)

In this stage, I built separate instances or individuals for each class. Instances are physical samples of the classes and reflect the actual entities in the real-world system. Some instances include:

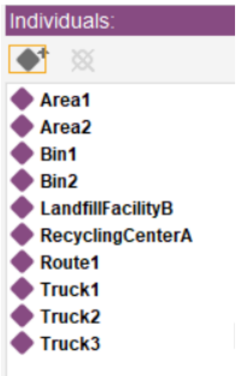

Fig 4. Instances

- *Location:* Instances like *Area1* and *Area2* represents the location.
- *Bins:* Instances such as *Bin1* and *Bin2* corresponds to bins.
- *Facilities:* Instances like *RecyclingCenterA* and *LandfillFacilityB*.
- *Routes:* Instances such as *Route1*, denoting collection routes with designated vehicles.
- *Vehicles:* Instances like *Truck1*, *Truck2* and *Truck3* denote certain garbage collecting trucks.

Creating instances allows the ontology to replicate real-world entities, making it feasible to reason about them and interact with external data sources (e.g., IoT sensors).

D. *Defining Rules and Reasoning*

After constructing classes, properties, instances, the next stage was to define reasoning rules. These rules regulate the system's behavior and enable ontology to automatically infer latest information depending on established criteria. For instance:

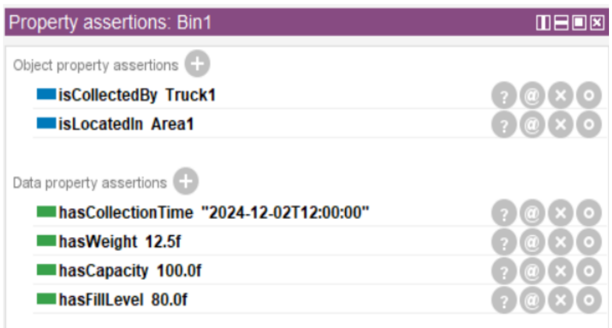

Fig 5. Rules

Using reasoning engine such as *HermiT*, I was able to apply these principles to infer new information and automate decision-making in the system. The reasoning process also improves the discovery of faults, such as overflowing trash or inefficient paths.

E. *Visualization using OwlViz*

In this stage, the *OwlViz* plugin was deployed to graphically show the connections, classes, properties, and instances inside the ontology. *OwlViz* is an excellent visualization tool built for expressing and studying ontologies produced using the Web Ontology Language (OWL). This picture enabled enhanced comprehension of the hierarchical structure and logical relationships in Intelligent Urban Waste Management Ontology [9].

Using *OwlViz* allows for the graphical depiction of crucial elements such as waste categories, smart bins, cars, routes, and processing facilities. This stage gave insights into how various pieces interact inside the system, supporting the analysis, debugging, and validation of the ontology's reasoning logic. The visualization method also verified that linkages and procedures were appropriately depicted and matched with real-world events.

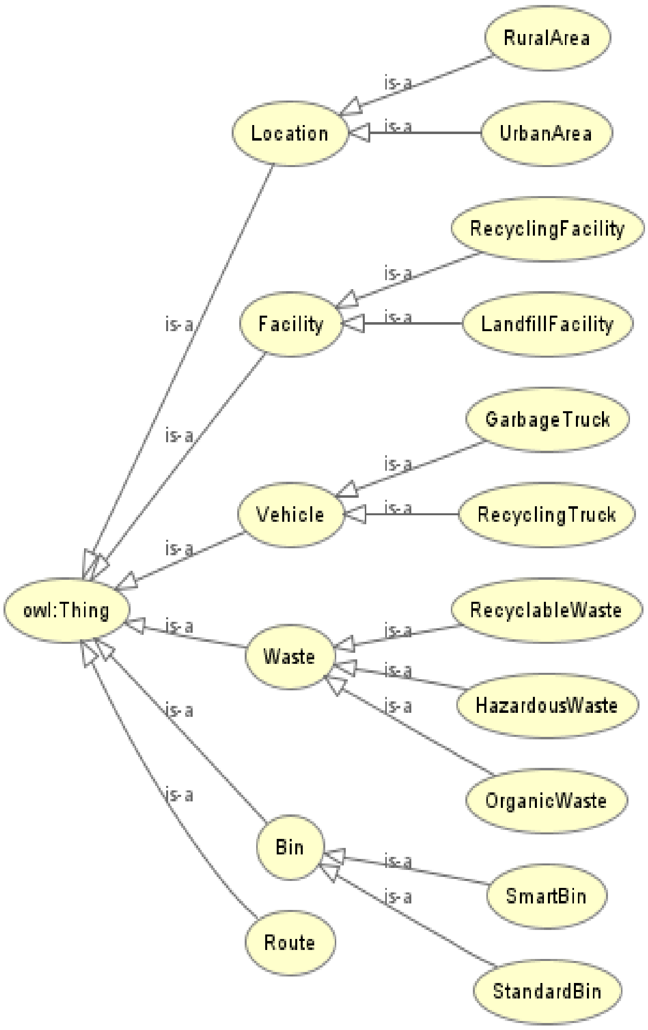

Fig 6. Class hierarchy of Ontology in Protégé.

VI. Evaluation: Inferred Knowledge and Querying the Ontology

A. *Inferred Knowledge*

In framework of Intelligent Urban Waste Management System (UWMS), inferred knowledge serves a critical role in boosting the systems flexibility and intelligence. Ontology is meant to assist automated reasoning based on specified rules and interactions between various concepts, such as waste categories, bins, vehicles, and routes. Using reasoning engines like *HermiT*, the system may evaluate how successfully it infers new knowledge from the facts in the ontology. The major purpose of this reasoning is to infer certain situations and automate decision-making processes, which leads to more effective waste management operations [4].

Some of the primary categories of inferred knowledge within the system include:

Overflow Detection: The system infers whether a bin is overflowing by comparing its *hasFillLevel* data attribute to a predetermined threshold, such as 80%. This inferred information guarantees that overflowing bins are dealt swiftly, and collection routes are optimized for fast intervention

Route Optimization: The system infers the requirement for route changes or priority based on real-time bin data. For example, if a vehicle's route comprises bins reaching full capacity (over 80%), the system immediately reassigns or prioritizes that route to save fuel use and improve the collection process. This inference enables effective vehicle dispatching and reduces wasteful resource utilization.

Vehicle Allocation: The ontology also enables for dynamic vehicle allocation based on real-time trash levels and location data. If a garbage truck's route is near full capacity or if specific bins along its route are empty, the algorithm infers that a different vehicle could be better suited for the collection. This dynamic allocation saves operating expenses by ensuring cars are efficiently utilized and not overfilled or inefficiently dispatched.

Inferred information inside the UWMS helps automate choices related to overflow detection, route optimization, and truck allocation, leading to more effective and sustainable waste management procedures.

B. *Querying the Ontology*

Querying the ontology is a crucial aspect of analyzing the knowledge stored and inferred inside the Intelligent Urban Waste Management System. By querying the ontology using *SPARQL* (the standard query language for RDF data), I was able to extract key information to analyze the system's functionality and performance. These queries enabled for real-time examination of relationships, data retrieval, and reasoning outputs, offering insights into system behavior and decision-making processes. Below are some examples of important queries that were used to test the system:

a) Query 1: Overflow Bins

The purpose of this query is to discover any bins with a fill level more than 80%, indicating they are overflowing and require immediate care. The *SPARQL* query used is:

```
SELECT ?bin WHERE {
  ?bin ex:hasFillLevel ?level.
  FILTER(?level > 80)
}
```

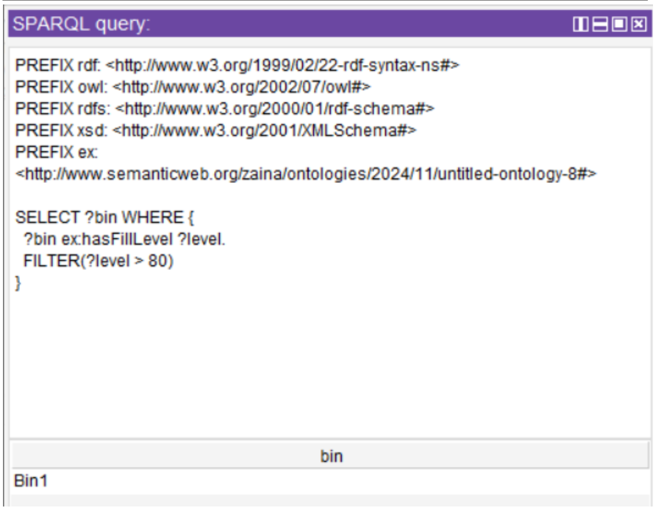

Fig 7. Overflow Bins

The consequence is that the system returns all bins labelled as "overflowing" based on their *hasFillLevel* attribute. This query helped evaluate if the ontology appropriately indicates bins that need urgent collection.

b) Query 2: Vehicle Allocation for Overflow Bins

This query aims to detect which trucks are assigned to certain routes inside the Intelligent Urban Waste Management System. The *SPARQL* query used is:

```
SELECT ?vehicle ?route WHERE {
  ?vehicle ex:isAssignedTo ?route .
}
```

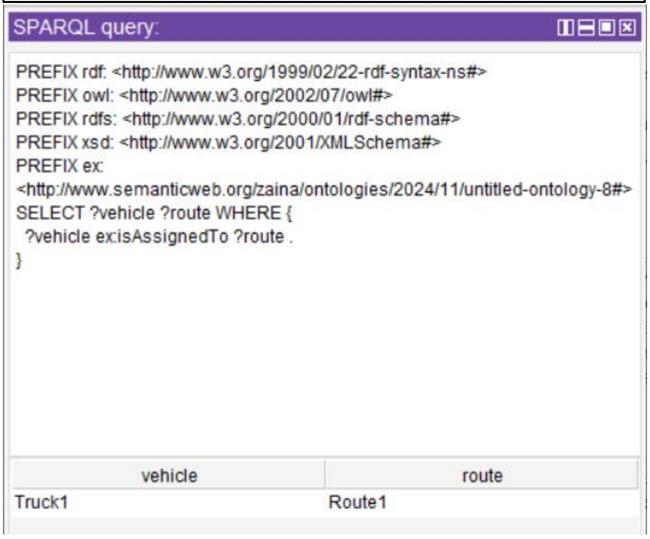

Fig 8. Vehicle Allocation for Overflow Bins

The result is that the system returns the cars and their matching allocated routes. This query helps verify whether the system appropriately matches cars with specified routes, guaranteeing accurate vehicle-route assignments inside the waste management system.

c) Query 3: Identifying Bin Locations

This query tries to determine the locations where different bins are positioned inside the waste management system. The *SPARQL* query used is:

```
SELECT ?bin ?location
WHERE {
  ?bin rdf:type ex:Bin .
  ?bin ex:isLocatedIn ?location .
  ?location rdf:type ex:Location .
}
```

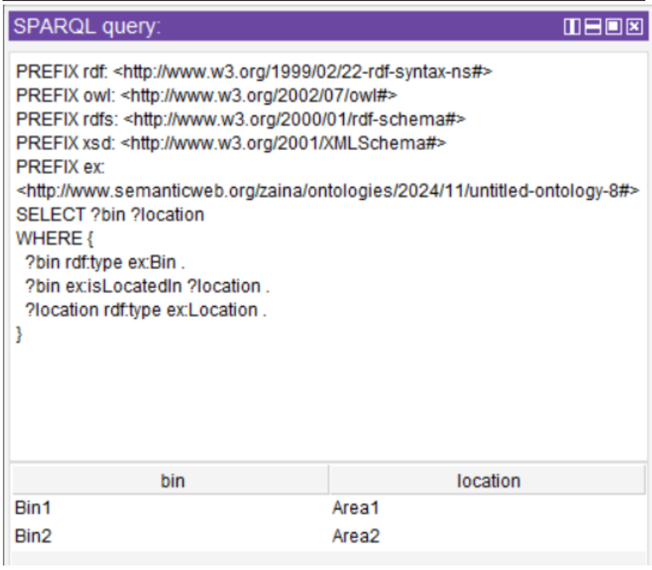

Fig 9. Identifying Bin Locations

The outcome is that the system returns the bins and their respective locations. This query helps to check that bins are accurately paired with certain places inside the system. It is beneficial for controlling the placement of bins across different locations, ensuring that the garbage collection process is spatially structured and that the system appropriately represents the real-world placement of bins.

d) Query 4: Route Optimization Based on Bin Fill Levels

This query seeks to determine ideal routes for garbage collection based on the fill levels of bins along those routes. The *SPARQL* query used is:

```
SELECT ?route
WHERE {
  ?route rdf:type ex:Route .
  ?route ex:hasBin ?bin .
  ?bin ex:hasFillLevel ?level .
  FILTER (?level > 80)
}
```

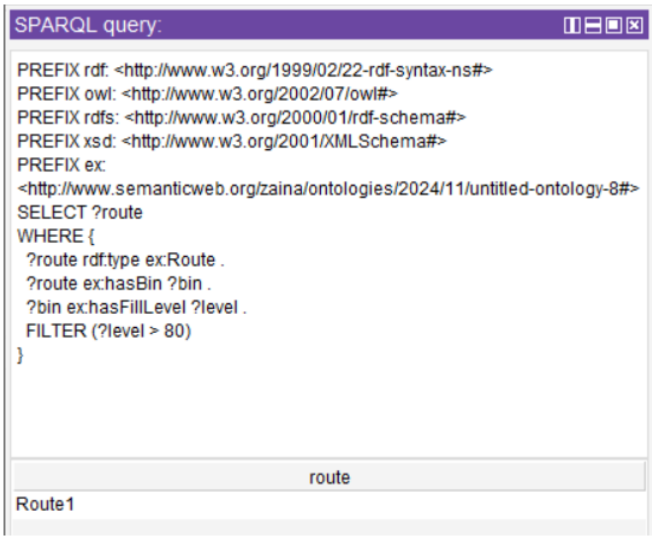

Fig 10. Route Optimization Based on Bin Fill Levels

The end result is that the algorithm returns routes that contain bins with high fill levels, suggesting the need for rapid collection. This query helped determine if the system could appropriately prioritize routes that required rapid action.

Conclusions

Intelligent Urban Waste Management System (UWMS) implies a significant improvement in urban garbage management, concentrating on efficiency, sustainability, and real-time flexibility. By employing ontology-based knowledge representation and reasoning, UWMS offers a structured framework that incorporates real-time monitoring, dynamic optimization, and informed decision-making. The system optimizes garbage collection efficiency by employing sensors in smart bins to monitor fill levels, enabling prompt collection and priority of high-load bins to minimize overflows. It automatically optimizes routes for garbage collection vehicles, factoring in real-time factors like traffic and bin status, hence minimizing fuel consumption and operating delays.

The ontology-driven system provides correct trash categorization and routing to appropriate processing facilities, boosting recycling efforts and reducing environmental pollution. This contributes to sustainable waste processing by encouraging the circular economy and minimizing the ecological imprint of trash disposal. Additionally, the system responds to changing conditions, such as overflow detection or vehicle unavailability, and is scalable across varied urban contexts, from tiny neighborhoods to major metropolitan regions.

UWMS encourages data-driven decision-making by giving actionable insights into operations, such as spotting overflowing bins or allocating cars to key routes. This leads to optimized resource usage and operational strategies. The consequent cost reductions, through lower fuel use, labor, and maintenance, boost economic efficiency.

Future advancements include incorporating sophisticated AI and machine learning to forecast garbage creation trends and further refine route efficiency. Expanding the system's capacity to manage unplanned occurrences and interact with larger urban infrastructure can yield even greater advantages. UWMS exhibits a forward-thinking approach to waste management, encouraging sustainable practices and building healthier urban environments.

References

[1] Gruber, T. R. (1993). A Translation Approach to Portable Ontology Specifications. Knowledge Acquisition, 5(2), 199-220.

[2] Shadbolt, N., Berners-Lee, T., & Hall, W. (2006). The Semantic Web Revisited. IEEE Intelligent Systems, 21(3), 96-101.

[3] Bizer, C., Heath, T., & Berners-Lee, T. (2009). Linked Data – The Story So Far. International Journal on Semantic Web and Information Systems (IJSWIS), 5(3), 1-22.

[4] Kultsova, Marina & Rudnev, Roman & Anikin, Anton & Irina, Zhukova. (2016). An ontology-based approach to intelligent support of decision making in waste management. 1-6. 10.1109/IISA.2016.7785401.

[5] Younesi, Abolfazl & Fard, Hamed & Belal Yengikand, Alireza & Pezeshki, Vahid. (2022). Survey on IoT-based waste Management Systems. 162-167. 10.1109/ICWR54782.2022.9786239.

[6] Kadus, Tejashree & Nirmal, Pawankumar & Kulkarni, Kartikee. (2020). Smart Waste Management System using IOT. International Journal of Engineering Research and. V9. 10.17577/IJERTV9IS040490.

[7] Psyllidis, Achilleas. (2015). Ontology-Based Data Integration from Heterogeneous Urban Systems: A Knowledge Representation Framework for Smart Cities.

[8] Sosunova, Inna & Porras, Jari. (2022). IoT-Enabled Smart Waste Management Systems for Smart Cities: A Systematic Review. IEEE Access. 10. 1-1. 10.1109/ACCESS.2022.3188308.

[9] Protege Project, "OWLviz," GitHub. [Online]. Available: https://github.com/protegeproject/owlviz. [Accessed: Dec. 2, 2024].

[10] Hasan, Mohammad Kamrul & Khan, Muhammad & Issa, Ghassan & Atta, Ayesha & Akram, Ali & Hassan, Muhammad. (2022). Smart Waste Management and Classification System for Smart Cities using Deep Learning. 1-7. 10.1109/ICBATS54253.2022.9759087.

Working Ontology

The following attachment as object has the working ontology:

OWL.owx