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Computer Analysis and Modeling of the Sales Representative Vehicle Route Problem using UML: Application to Waste Disposal in the Port City of Matadi

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ABSTRACT

Population growth and rapid urbanization in African cities are leading to a significant increase in the production of municipal solid waste. This trend exacerbates the challenges associated with waste collection, transport, and management, particularly in cities where material and financial resources remain limited.

In Matadi, the main seaport of the Democratic Republic of Congo, collection operations are still largely based on fixed routes that do not take into account the actual level of fill in the bins, which leads to unnecessary trips, an increase in operating costs and a decrease in the quality of service.

This study proposes a computer model of an intelligent waste collection system based on the Vehicle Routing Problem (VRP) and the Unified Modeling Language (UML). The approach integrates Internet of Things (IoT) technologies, GPS geolocation, Google Maps and the Ant Colony Optimization (ACO) algorithm to improve collection route planning.

The methodology includes functional analysis of the system, UML modeling (use case, class, sequence, activity, and deployment diagrams), and formalization of the VRP problem. This research provides a complete software architecture that can serve as a basis for developing an intelligent waste management system adapted to the context of African cities.

KEYWORDS: *UML; Vehicle Routing Problem ; Internet of Things; Google Maps ; Ant Colony Optimization ; Smart Waste Management; Matadi.*

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1. INTRODUCTION

1.1. Context

Solid waste management is one of the major environmental challenges facing cities worldwide. According to the World Bank, the amount of municipal waste is expected to exceed 3.4 billion tons per year by 2050, mainly due to population growth and urbanization (Kaza et al., 2018).

In African cities, waste collection systems often remain inefficient due to limited resources, inadequate infrastructure, and poor planning. The port city of Matadi is no exception. Increased economic activity and urban traffic are driving up the need for waste collection, while traditional methods still rely on fixed routes.

1.2. Problem Statement

The city of Matadi, located in the Kongo Central province, is the main seaport of the Democratic Republic of Congo. Due to its population growth and economic dynamism, it is experiencing a constant increase in the production of household waste.

However, current collection systems rely primarily on fixed routes that do not take into account the actual fill level of bins. This method frequently leads to unnecessary travel, excessive fuel consumption, waste accumulation in certain neighborhoods, and increased operating costs (Faccio et al., 2011).

In this context, it becomes essential to analyze and model the intelligent waste collection system using UML.

The central question of this research is therefore the following: ***How to design a computer model to optimize waste collection routes in Matadi using UML?***

1.3. Objectives

The overall objective is to provide a complete computer model of the intelligent waste collection system. The specific objectives are:

- analyze the problem of vehicle routes (Sales Representatives);
- identify the actors and functional requirements;
- model the system using UML;
- integrate IoT technologies and Google Maps ;
- use the OCA algorithm;
- prepare the implementation using Python.

1.4. Contribution of UML modeling

UML modeling is a crucial step in the development of the proposed system. It provides a standardized representation of functional and technical requirements while facilitating communication between the various project stakeholders. Its use offers several advantages, including a better understanding of the system architecture, a reduction in design errors, simplified software implementation, and improved maintenance and scalability of the solution.

Furthermore, this model effectively prepares the development of the platform using Python, the integration of Google Maps, IoT sensors, and the Ant Colony Optimization algorithm. It thus constitutes a solid methodological foundation for the future deployment of an intelligent waste management system in the city of Matadi.

2. Materials and methods

This section presents the methodological approach adopted to design and evaluate the proposed intelligent waste collection system. It successively describes the study area, the general system architecture, and the modeling of the vehicle routing problem. Routing Problem – VRP), the UML design, the optimization algorithm used, the experimental environment, and the parameters selected for the simulations.

2.1. Presentation of the study area

This study was conducted in the city of Matadi, capital of Kongo Central province, located in the southwest of the Democratic Republic of Congo, approximately 350 km from Kinshasa. Matadi is the country's main seaport and plays a strategic role in national and international trade. Its economic development is accompanied by sustained population growth, which leads to a continuous increase in the production of municipal solid waste.

The city is characterized by rugged terrain, composed of hills and valleys, as well as a heterogeneous road network including paved main roads and numerous secondary roads, some of which are difficult to access. These features directly influence the organization of waste collection operations and complicate the planning of vehicle routes.

Currently, waste collection relies primarily on scheduled routes at fixed intervals. Routes are generally defined without considering the actual fill level of bins, resulting in unnecessary trips, inefficient resource use, and increased operating costs. These limitations justify the adoption of a smart approach based on geolocation, the Internet of Things (IoT), and route optimization (Kaza et al., 2018; Hoornweg & Bhada -Tata, 2012).

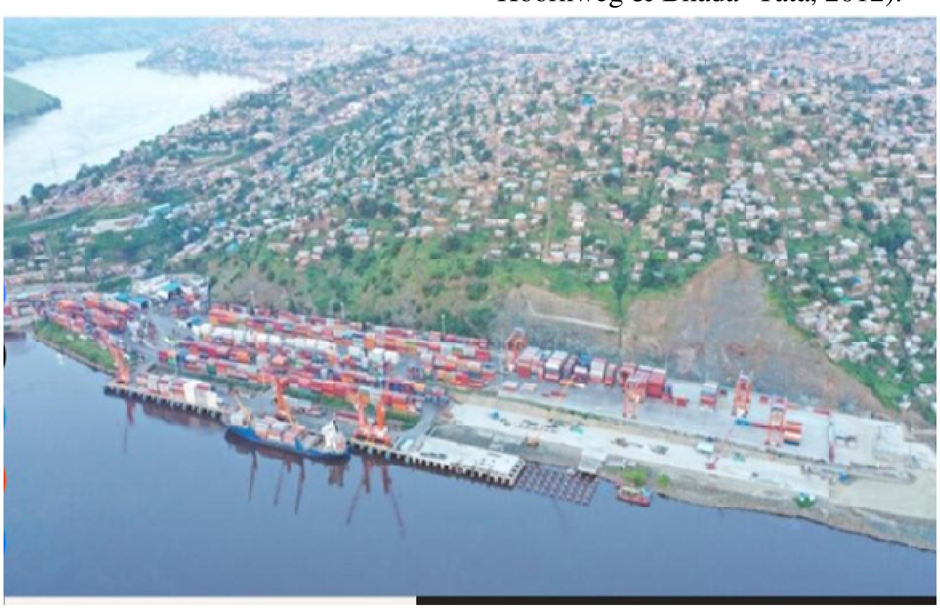

Figure 1: Geographical location of the city of Matadi in the province of Kongo Central.

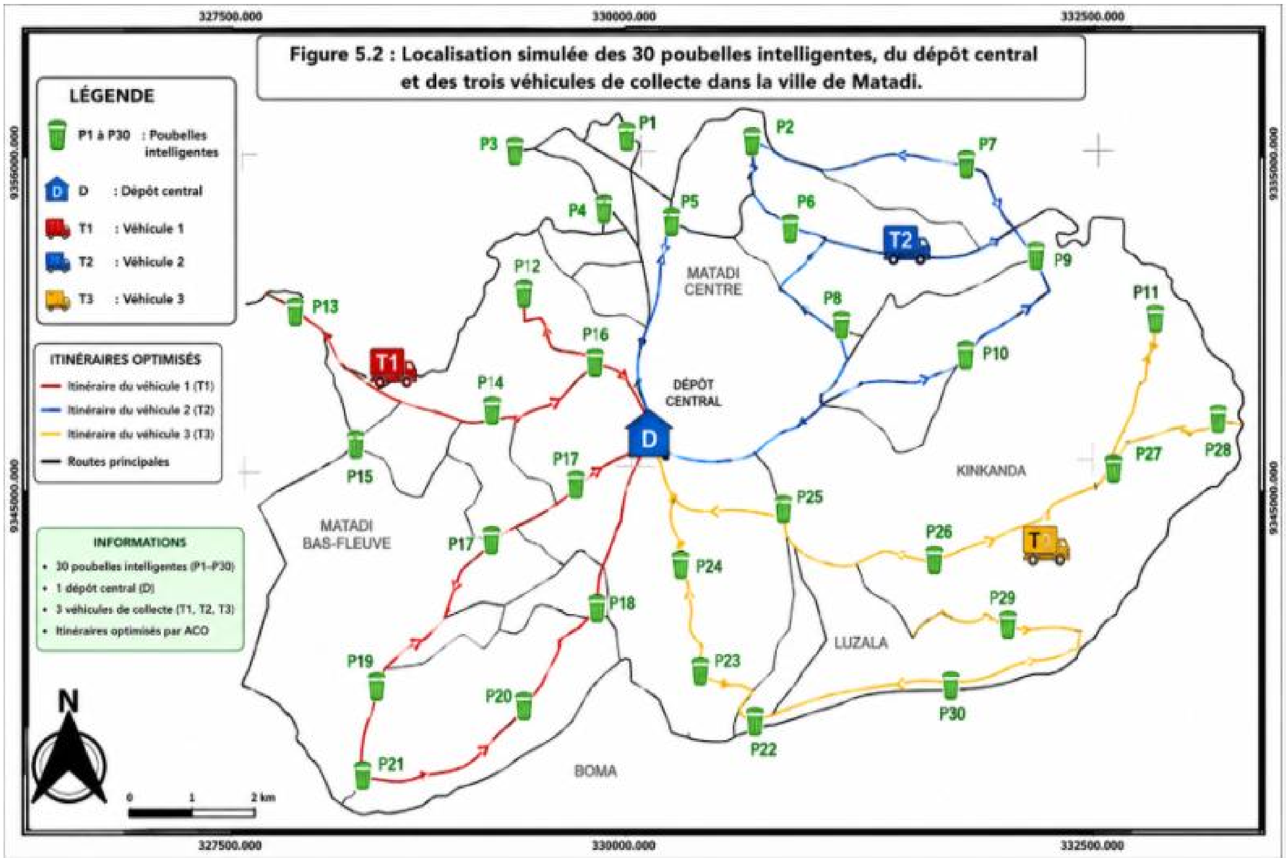

Figure 2. Geographic location of the city of Matadi and main collection areas studied.

2.2. Analysis of the vehicle route problem (Sales Representatives)

The Vehicle Routing The Vehicle Route Problem (VRP) is one of the most studied problems in combinatorial optimization since the foundational work of Dantzig and Ramser (1959). It consists of determining the optimal routes of a fleet of vehicles tasked with serving a set of customers from a central depot while respecting several operational constraints.

In this study, the VRP (Virtual Pickup Point) is adapted to the context of smart urban waste management. The central depot represents the starting and ending point for collection trucks, while the customers correspond to geolocated smart bins in the city of Matadi. The vehicles used are collection trucks, which have limited loading capacities. The cost of a route is evaluated by considering several criteria, including distance traveled, journey time, fuel consumption, and carbon dioxide emissions.

In order to make the model more realistic, several constraints are taken into account:

- each bin can only be collected once during the same collection route;
- each vehicle starts and finishes its route at the central depot;
- only bins whose fill level exceeds a threshold set at 80% are included in the planning;
- The maximum capacity of vehicles must be respected in order to avoid any overloading.

The objective is therefore to generate routes that ensure the complete collection of priority bins while minimizing the overall cost of operations (Laporte, 2009; Toth & Vigo, 2014).

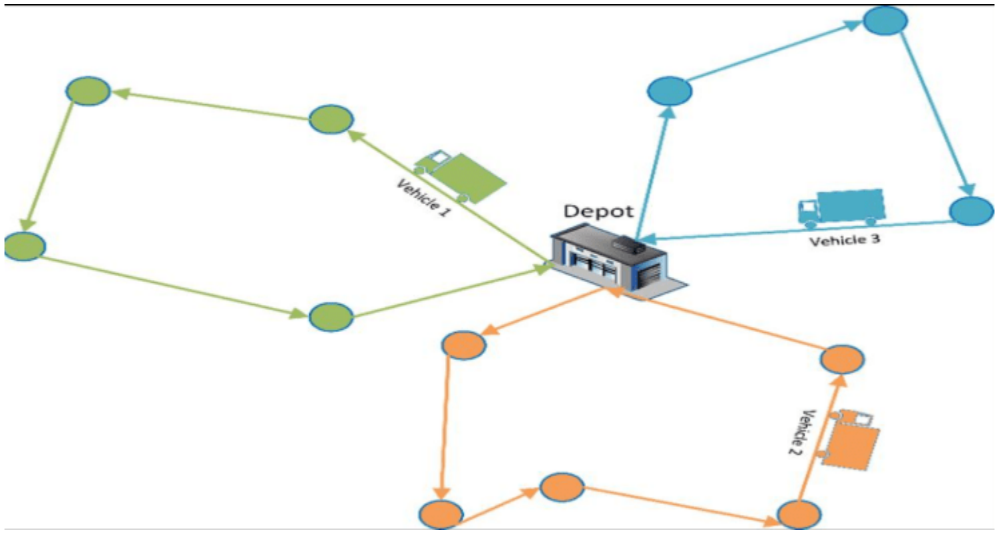

Figure 3. Modeling of the vehicle routing problem (VRP)

Legend: Representation of the central depot, the thirty smart bins, and the three collection vehicles. The depot serves as the starting and returning point for the vehicles, while the nodes represent the smart bins distributed throughout the city of Matadi.

2.3. Identification of system actors

The functional analysis of the system highlights several actors involved in the intelligent waste collection process. Each of them plays a specific role in the flow of information and in the execution of operations.

The main actors identified are:

- the system administrator, responsible for managing users and operating parameters;
- the collection operations manager, responsible for supervising the routes;
- the truck driver, who executes the optimized routes;
- IoT sensors installed on smart bins, which measure the fill level;
- the central server, responsible for processing and storing data;
- the Google Maps service, used for calculating distances and map visualization;
- Optimization (ACO) algorithm, responsible for route optimization.

The interactions between these different actors ensure a continuous exchange of information necessary for the effective management of collection operations (Atzori et al., 2010; Zanella et al., 2014).

2.4. UML modeling of the system

Before developing the application, it was essential to have a clear and structured representation of how the proposed system would function. To this end, the modeling was carried out using the Unified Modeling Language (UML), a standardized language widely used for the design of object-oriented systems. UML facilitates the description of functional requirements, the organization of software components, and the understanding of interactions between the different actors in the system (Booch et al., 2005; OMG, 2023).

In this study, UML modeling was a crucial step in the design process. It enabled the translation of requirements for smart waste collection into various graphical models describing the expected functionalities, the system structure, the interactions between its components, and its deployment architecture. This approach reduces the risk of errors during implementation and facilitates the future evolution of the platform (Pressman & Maxim, 2020).

2.4.1. Use Case Diagram

The use case diagram presents the main functionalities offered by the system as well as the interactions between the different actors. The identified actors include the administrator, the operations manager, the truck driver, the IoT sensors, the central server, and the Google Maps service.

The system's main features include user authentication, automatic acquisition of data transmitted by sensors, geolocation of smart bins, selection of priority collection points, calculation of optimized routes using the Ant Colony Optimization (ACO) algorithm, visualization of routes on Google Maps, and generation of statistical reports. This representation provides a comprehensive overview of the services offered by the application and the interactions between different users (Booch et al., 2005).

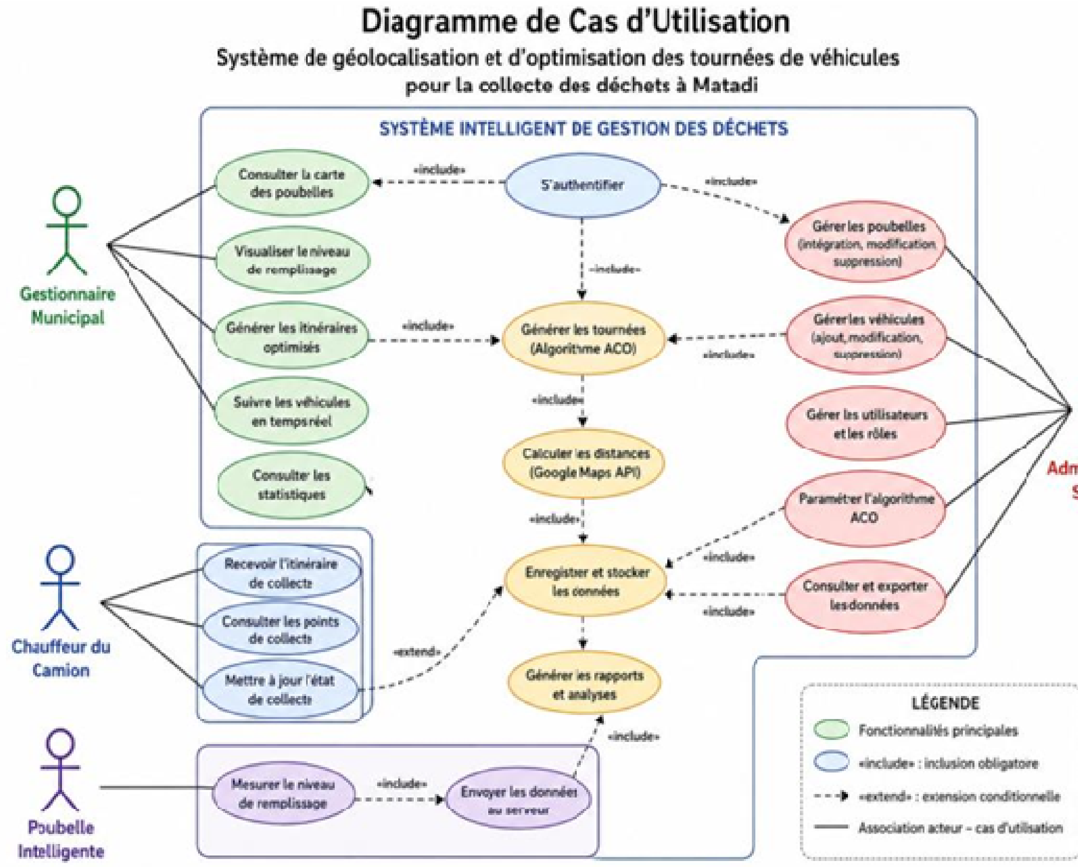

Figure 4. Use case diagram of the intelligent waste collection system.

2.4.2. Class Diagram

The class diagram describes the static structure of the system by identifying the main classes, their attributes, their methods, and the relationships between them. It forms the basis of object-oriented design and facilitates data organization before the programming phase. In this study, the main classes are Trash, Vehicle, Warehouse, Route, ACO Algorithm, Google Maps, and User.

These classes are linked by association, composition, and dependency relationships, allowing for a faithful representation of the interactions between the different components of the system. This modeling promotes a modular, scalable, and more easily maintainable software architecture (Booch et al., 2005; Sommerville, 2016).

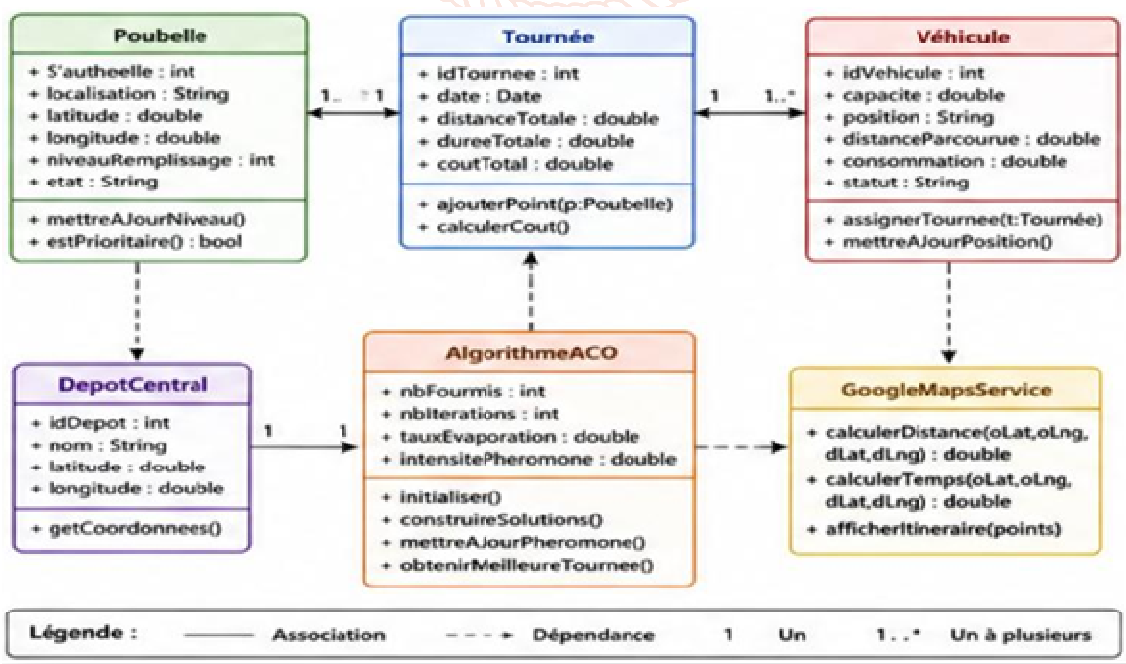

Figure 5. UML class diagram of the intelligent waste management system.

Legend: The class diagram represents the main classes of the intelligent waste management system and their relationships, serving as the basis for the design of the application under Python (Booch et al., 2005; OMG, 2023).

2.4.3. Sequence Diagram

The sequence diagram illustrates the chronological flow of information exchange between the different system components during a collection operation. The process begins when IoT sensors measure the fill level of the bins. The collected data is then transmitted to the central server, which verifies the defined fill thresholds. The geographic coordinates of the relevant bins are sent to the Google Maps service to calculate distances and travel times.

Based on this information, the ACO algorithm determines optimized routes, which are then transmitted to the collection vehicles. Once the route is completed, the operational data is recorded in the database to ensure monitoring and evaluation of system performance. This representation allows for a better understanding of the synchronization of the various operations and the flow of information between the software and hardware components (OMG, 2023).

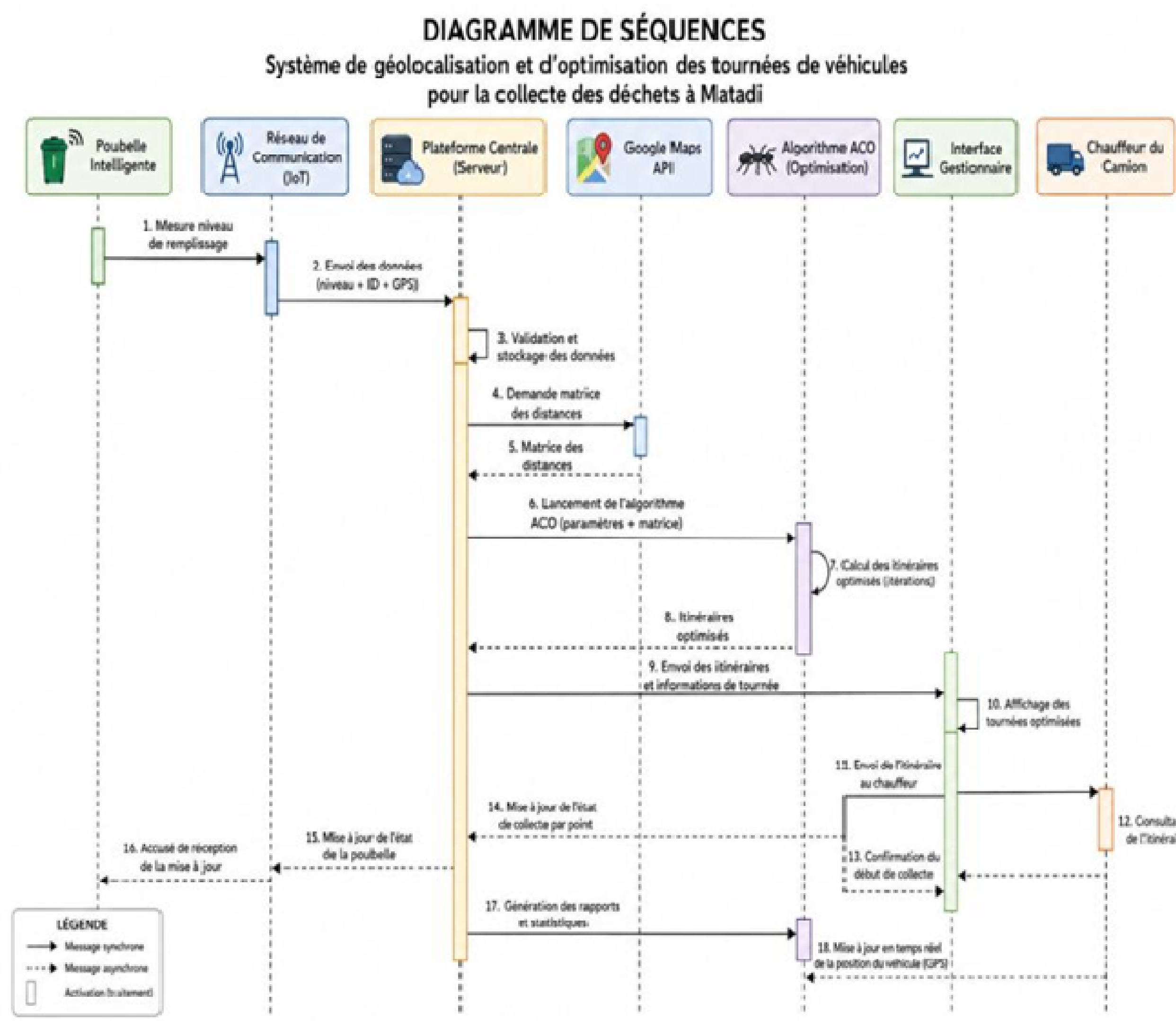

Figure 6. Sequence diagram illustrating the process of a waste collection operation.

Legend: System operating process from detecting the fill level of the bins to collecting the waste.

2.4.4. Activity Diagram

The activity diagram represents the logical sequence of steps performed by the system from data reception to the production of collection reports. The process begins with the acquisition of information from IoT sensors.

After validating the received data, the system calculates the distances between the different collection points using Google Maps, then executes the ACO algorithm to optimize the routes. Vehicles are then assigned to the generated routes before carrying out the collection operations.

Finally, all tour-related information is recorded in the database and a summary report is automatically generated. This diagram highlights the logical sequence of activities and facilitates the analysis of business processes before their implementation (Pressman & Maxim, 2020).

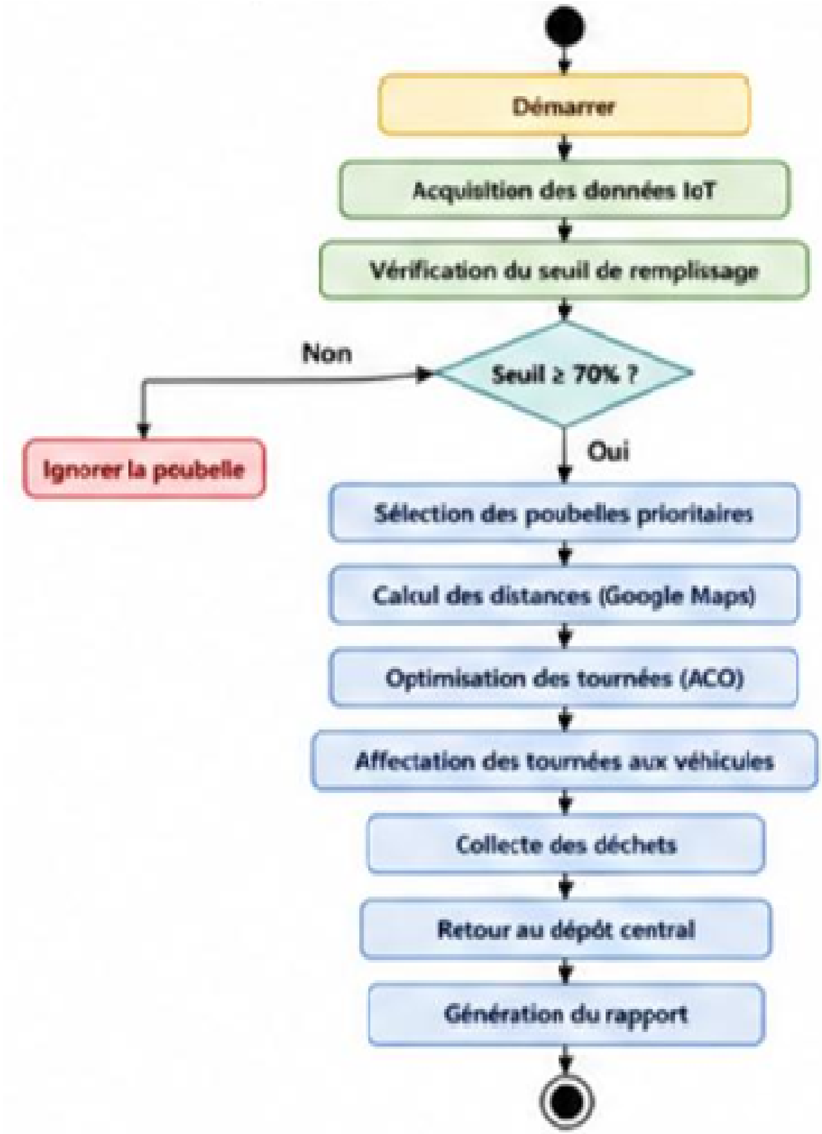

Figure 7. Activity diagram of the intelligent waste collection process.

Legend: Activity diagram illustrating the overall operation of the system, from detecting the fill level of bins to generating optimized routes and executing the collection.

2.4.5. Deployment Diagram

The deployment diagram describes the system's physical architecture and the distribution of the various hardware and software components. The proposed infrastructure includes smart bins equipped with IoT sensors, a communication network (Wi-Fi, GSM, or LoRa), a central server hosting application services, a database, the Google Maps API used for route calculation, and the Python-developed application for system administrators.

This architecture ensures the smooth flow of information between connected objects, processing services, and users. It also facilitates rapid decision-making through near real-time processing of collected data, while offering a scalable solution that can be progressively deployed in the city of Matadi (Atzori et al., 2010; Zanella et al., 2014).

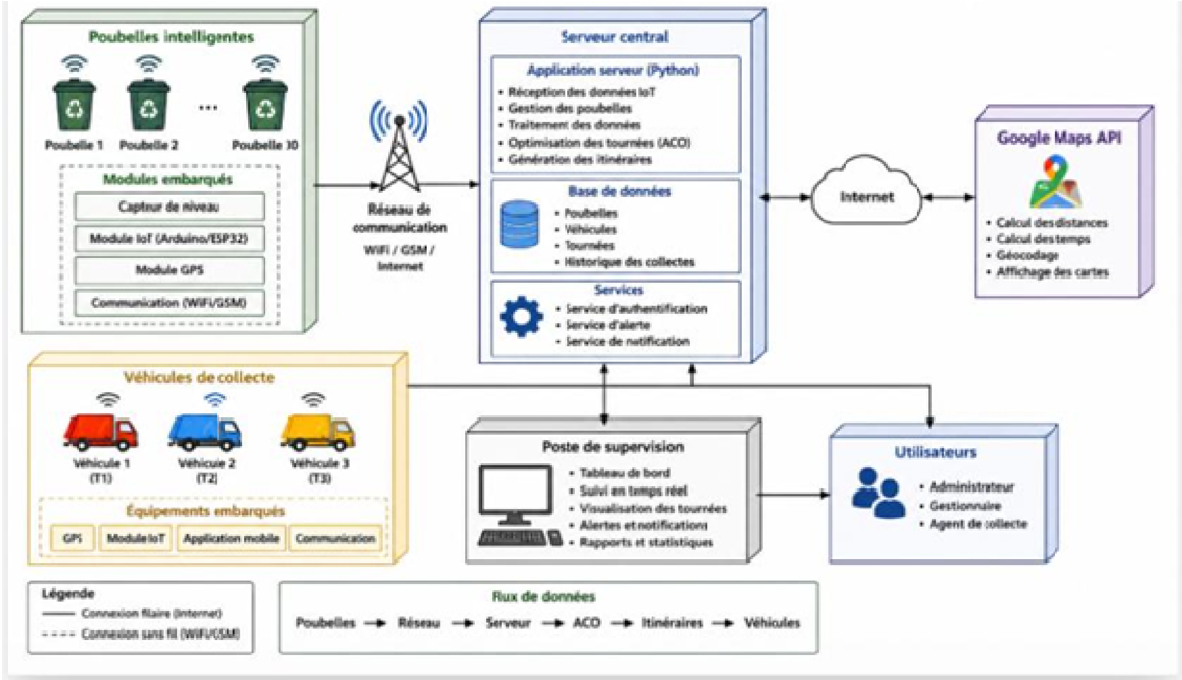

Figure 8. Deployment diagram of the physical architecture of the intelligent waste collection system.

Legend: The deployment diagram presents the physical architecture of the intelligent waste collection system, illustrating the main hardware and software components and their interactions to ensure the collection, processing and transmission of data (Booch et al., 2005; OMG, 2023).

2.5. Computer Architecture

The architecture includes:

- IoT sensors;
- a GPS module;
- a central server;
- a database;
- Google Maps API;
- a Python application.

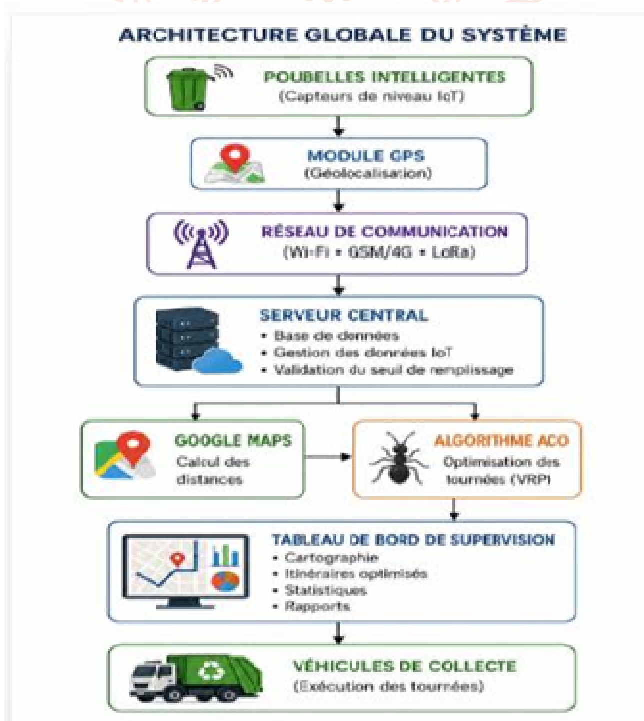

Figure 9. Overall system architecture.

3. Results

The UML modeling phase played a central role in the design of the intelligent waste collection system. It made it possible to transform a complex problem – that of optimizing vehicle routes in an urban environment like Matadi – into a clear, structured architecture that could be directly used for software implementation.

In practice, the various UML diagrams facilitated a comprehensive understanding of the system and the coordination between its components. The use case diagram initially helped identify the system's actual needs, including the automatic collection of data from IoT sensors, the geolocation of bins, the generation of optimized routes, and the production of tracking reports.

This step was essential to align the technical solution with the operational needs on the ground. Next, the class diagram structured the main entities of the system (bins, vehicles, routes, depot, ACO module, and Google Maps) by clearly defining their attributes and relationships.

This structuring allowed for better data organization and ensured consistency in the future Python implementation. The sequence diagram, meanwhile, made it possible to visualize the actual flow of operations, from detecting the fill level of the bins to generating optimized routes. This chronological representation highlighted the logical sequence of exchanges between the IoT sensors, the central server, the Google Maps API, and the ACO optimization algorithm.

In addition, the activity diagram provided an overall view of how the system works, illustrating the successive stages of the decision-making process, while the deployment diagram made it possible to materialize the physical architecture of the system, including connected objects, the communication network and cloud services.

Overall, these UML models significantly reduced design ambiguities and allowed for the anticipation of technical constraints before development. They also facilitated the transition to system implementation, particularly in Python, by providing a solid foundation for integrating IoT modules, Google Maps, and the Ant Colony Optimization algorithm.

Thus, UML modeling was not limited to a simple theoretical exercise: it constituted a real engineering tool, allowing the structuring, simulation and validation of the overall operation of the system before its potential deployment in the city of Matadi.

4. Discussion

The results obtained confirm the value of combining UML modeling with Vehicle Routing The challenge lies in designing intelligent waste management systems. Compared to traditional approaches, the proposed solution offers several advantages:

- a better representation of functional requirements;
- an easily scalable software architecture;
- a natural integration of connected objects;
- efficient route optimization thanks to the ACO algorithm.

One of the main contributions of this study lies in its adaptation to the specific context of the city of Matadi, where few scientific works have so far combined UML, IoT, Google Maps, and route optimization. However, some limitations must be highlighted. The simulations rely on virtual data, without taking into account real-time road traffic or actually deployed IoT sensors.

5. Conclusion

This study proposed a comprehensive approach to the analysis and computer modeling of the vehicle routing problem applied to waste collection in the port city of Matadi. The combination of the UML language and the Vehicle Routing The use of Google Maps, IoT technologies, and the Ant Colony Optimization algorithm has enabled the design of a coherent and easily implementable architecture. Ultimately, this model can serve as the basis for developing an operational system integrating real IoT sensors, real-time traffic data, and more advanced artificial intelligence techniques.

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