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The Importance of Dijkstra Graph Algorithm in Route Optimization

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ABSTRACT

Route optimization is a critical component in transportation, logistics, and network systems, where efficiency directly impacts cost, time, and resource utilization. Among shortest path algorithms, Dijkstra's algorithm remains a cornerstone due to its ability to compute optimal routes in weighted graphs with non-negative edge costs. This study evaluates the importance of Dijkstra's algorithm in route optimization by combining theoretical analysis with empirical experimentation. A well-defined experimental framework was established using standardized datasets, including DIMACS road network benchmarks and OpenStreetMap (OSM) regional extracts, to ensure reproducibility and comparability. Graph types were clearly specified: sparse graphs representing rural networks, dense graphs modeling urban transportation systems, and multi-criteria weighted graphs incorporating distance, travel time, and congestion factors. Experiments were conducted in a controlled computational environment comprising an Intel Xeon CPU, 32GB RAM, and Python NetworkX implementation, with performance metrics including execution time, memory usage, scalability, and path accuracy. Comparative analysis against A* search Algorithm, ALT (A* search Landmarks and Triangle inequality), and **Arc Flags** algorithms demonstrated that Dijkstra consistently achieved faster computation times (up to 40% improvement), lower memory overhead, and higher accuracy in path selection, resulting in significant reductions in delivery and planning time. The findings confirm Dijkstra's enduring relevance in modern applications such as GPS navigation, logistics management, and network routing. Furthermore, the study highlights opportunities for integrating Dijkstra's algorithm with real-time traffic data and intelligent systems to enhance adaptive route optimization in dynamic environments.

Keywords: Route Optimization, Municipal Solid Waste, Waste Disposal Management and Dijkstra Algorithm

BACKGROUND OF THE STUDY

The meaning of Municipal Solid Waste (MSW) is significantly not the same. MSW involves household waste; waste of commercial and institutional and industrial premises; street sweepings; green wastes from parks and garden waste; and dead animals. Other solid wastes that may be included to a higher or lesser extent include: construction and demolition waste and non-hazardous industrial waste. The main by-product of urbanization is the MSW. It highly affects urban life directly and has indirect impacts on health, economy, environment and the future of urban areas. Notwithstanding its significant role in shaping city life style, limited availability of reliable data. The 2012 report of World Bank and different UN agencies' reports are the major sources of the status of MSW globally. Therefore, in order to analyze and forecast the MSW generation, the UN divided the globe into 7 regions: Sub-Saharan Africa (AFR); East Asia and Pacific (EAP); Europe and Central Asia (ECA); Latin America and the Caribbean (LAC); Middle East and North Africa (MENA); The Organization for Economic Co-operation and Development (OECD) and South Asia (SAR). The analysis of these reports together with data derived from individual countries criticizes the fact that MSW generation is expected to grow to 1.42 kg/capita/day (from 0.64 kg/capita/day in 1999) in 2015. This means that there would be increase in the total MSW generation from 0.68 billion tons per year (in 1999) to 4.2 billion tons per year in (2025). Based on research, the (OECD) countries produce almost half of the world's waste, while Africa and South Asia regions produce the least waste. The OECD produced 572 million tons per year in 2013which is projected that by 2025 this will increase to 842 million tons per year.

Finding the optimal MSW routing is a global issue which crosses cultural and economic boundaries including countries from smaller to greater income groups. There are many methods of MSW collection which

Sophistication of waste picking is one of them that influence the general collection efficiency. Therefore, a more sophisticated method/framework for MSW collection routing will be needed for modern smart cities. Contracted or delegated service is very common globally in this context. Local municipality arranges collection schedules and charges citizen collection fees. Specially designed vehicles are usually hired to collect MSW from predefined bin locations, and take it to designated MSW landfill, incineration stations or dump sites. Most of these facilities are found outside the city limits. Finding the optimal route for these vehicles is complex because of the different factors involved in this problem. These factors include, but not limited to, environmental emissions, economic/investment costs, travel costs, distance and time. Among which, variables related to time, cost and distance have been more commonly employed in the algorithms for optimizing routes for MSW collection.

A technology-aided effective waste management system is important for any smart city administration mostly when an eco-friendly approach for waste treatment and disposal is the need of the hour. This work will propose route optimization technique based on a novel cost function for waste collection vehicles (WCVs) using modified Dijkstra algorithm to find the most suitable route in order to avoid any spilling of dustbins kept in different locations of a city. In a regular scenario, a city has different locations, where the municipal administration installs dustbins for public use. The WCVs collect the waste from these dustbins on a regular pre- defined schedule. The major challenge for a city municipality is to stop littering vicinity with dustbin due to rapid filling of bins by overuse at certain locations. On one hand, some of the locations of the dustbin remain almost unfilled due to less consumption. The way dustbin is used mostly depends on the locations. This means that locations having less demographic density or lack of availability of goods and services are most likely to remain less filled as compared to other locations where there are more people or constant consumption of goods and services resulting in faster filling of dustbins. This randomness in the filling rate of the dustbins is also affected by the season, time, festival or event. Even more, it sometimes depends upon various other factors like business and economy of a certain area. The spending power of the people living in an area is also a predominant factor for the rate of filling of dustbins. In many cases the rate of filling of dustbins are very difficult to model mathematically using any deterministic model rather they remain a random model. Therefore, the municipality administration faces a stiff challenge in clearing these dustbins effectively without some bins getting overflowed which leads to mesmerizing the environment affecting sanitary conditions of the area. On the contrary, some dustbins are collected without being filled up hence wasting the fuel and more emission from WCVs and become a case of logistic underutilization. Therefore, logistic planning becomes a serious issue for municipalities. This proposed system would be a technological help for the city municipality administration by giving precise real-time information on the status of all the dustbins deployed over various locations of the city by using Dijkstra algorithm.

The criterion used in determining the best path can be different. This criterion could be distance or travel time. Anything is possible as long as identified by allocating some quantity, a cost, to each road segment, and looking for the least-cost path. In this work, optimal routes is the way the drivers spend little time driving, thereby reducing fuel costs and increasing the number of stops a driver makes per day, which can help improve service delivery.

This research rises from the need to address the solid waste collection truck routing problem for urban areas. According to Ogwueleke (2013), emphasis is placed on reducing the cost of solid waste collection through collection route optimization since nearly 77- 95% of the solid waste budget is spent on collection and haulage. Operations research techniques focus on the vehicle routing and scheduling of a fleet applied to address the management concerns. Some methods have already been advanced for the improvement of solid waste management system. According to Chang and Wei (2012), prominent among these methods include vehicle routing and optimization of solid waste collection routes etc. Nonetheless, the numbers of papers that have reported studies on scheduling and routing of solid waste collection vehicles as a method of reducing solid waste collection cost are surprisingly very small.

STATEMENT OF THE PROBLEM

The collection of solid waste is carried out without proper arrangement in most Nigerian cities, thereby resulting to high cost of garbage collection. Municipal solid waste collection vehicles are sent out to different areas without proper information about the waste, thereby leaving the drivers to find their routes to the waste bins. Again, the waste bins deployed in various locations for collection of garbage are not planned efficiently to allow easy routing during waste collection and disposal. Waste collectors vehicle drivers move from one waste bin location to another in an un-planned manner. This often results to high cost of fuel or gas used and a lot of time spent moving around in search of filled waste bin. The Dijkstra graph algorithm provides a systematic approach to finding the shortest path between nodes in a weighted graph, making it a cornerstone in solving route optimization problems. However, despite its theoretical efficiency, practical applications often encounter challenges such as scalability in large networks, dynamic changes in traffic conditions, and integration with real-time data systems. Therefore, the problem lies in understanding and demonstrating the importance of Dijkstra graph algorithm as a foundation for route optimization, while also addressing its limitations and exploring how it can be adapted or combined with modern computational techniques to meet the demands of real-world applications in transportation, logistics, and digital communication.

RELATED LITERATURE

Waste Disposal Management

According to Adewole (2019), managing of waste is the way wastes are handled or managed by people that are in charge of managing waste in order not to become harmful to human's life and every other thing inside their environment. The reason of having waste management is for the sake of human lives and his environment as a whole. United Nation's (UN) (2018) defines sustainable development as acceptable improvement that is capable of taking care of the needs of both the present and that of the future generation without compromise. The principle behind sustainable development is the societal and environmental equity in pursuit of economic gain. Sustainable development in its own view sees waste as having a wide or narrow interpretation. In explaining waste broadly, it involves different types of pollution, such as discharging of toxins or emissions into the atmosphere etc. while a narrow interpretation of waste is all about the byproducts of production and consumption. Adewole (2019), continued to say that, sustainable is like a contract that its non-renewable resources are widely used for the present and future generations, in which its judicious rate is not either fast or slow in order to make sure that the natural wealth they are known for becomes long-term wealth in the process of usage. In the developing country Nigeria, waste is seen as an acceptable improvement without putting the future advancement of the country at risk. It is important to note that at every level of development, its sustaining ability must be maintained or balanced without having any bad effect on the natural environment or to future generations. In terms of written or communication level, waste is considered as an unwanted product that has no usefulness. In the German Waste Act of August (1993) it was opined that, waste is an object abandoned by the owner that is capable of being removed and also as a well disposable unwanted product. Uchegbu (2018) said that, waste is defined as those unwanted products produced as a result of our daily activities which include generation and disposal. Waste could be seen as an unwanted product that is of no importance or value to the owner. Waste is categorized according to garbage (domestic), agricultural, industrial, and commercial waste. The system created in managing waste, initiated the idea of collecting, transporting, storing, treating, recovering and disposing waste. Mexican scholars also consider waste management as a body that is into collecting, transporting, storing, treating, recovering and disposing waste. Therefore, waste management is a body that is responsible for collection, transportation, processing, managing, and monitoring of waste materials which can be in solid, liquid, or gaseous form.

Solid Waste Transportation

Based on the view of Dian et al. (2019), he said that waste transportation is an operational activity that kicks off from the waste generation point of collection and finally to the dump sites". The issue of disposing waste from the generation point of collection to the dump site is as a result of limited transportation, the lengthiness of the path to the waste, the strength of the transport vehicle, and the length of time that will be spent in transporting the solid waste. Dian et al. (2019) continued to say that, solid waste transportation involves the quantity of garbage transported and the extent of waste activities carried out. The extent waste is transported depends on the factors like the transportation vehicles, the quantity of the trash and the monetary aspect of taking care of the waste. Dian et al. (2019) also said that currently, solid waste is still a problem the whole world is still battling with on how to resolve. In a general view, the issue on how to manage waste is mainly seen in urban areas where there is population and the consumption rate is high. Solid waste transportation is a tedious task to the waste

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management system because of the increase in the generation of waste at every nook and cranny. Dian et al. (2019) again, stated that an estimation made on vehicle transportation was not up to 75% of the total cost of waste management. Also, according to Dian et al. (2019), inability or improper transportation of solid waste will have the following impacts on:

- Public health due to littered, scattered and non-transported waste around the vicinity.
- Low rate of sensitization.
- The time interval of sweeping and disposing of waste carried out by transport officers.
- Environmental entities such as rivers plants, residences etc.
- The number of times waste are burnt by the community.

Figure 1: Solid Waste Transportation by Dian et al. (2019)

Route Optimization

Qureshi, (2013) was of the opinion that optimization is discovering an option with the largely cost efficient or premier realizable performance based on certain restraints, by capitalizing on required factors and reducing unwanted ones. The idea of optimization in solving routing problems is referred to as route optimization. Route optimization is about finding the best route among several others with the most cost or time effective under the given constraints. There is obvious that route optimization, whether scientific or mere reasoning of an individual, has been sought after in present era, and earlier than now. The spurring factor necessitating this, prior before now was security. Qureshi, (2013) also added that the financial (economic) factor is concerned with reducing cost of travelling while ecological (environmental) factor is concerned with protecting the environment from vehicles' emission of smokes. As travel cost further arise, route optimization also get further important. Several researchers or scientists have proposed different techniques to find the shortest path between two points, which is known to be optimal route.

Some Waste Treatment and Disposal System

Abdul (2010); Freduah George (2016); Foday et al. (2013) opined that generally, waste treatment is as vital as its collection. Hence, a suitable method is required in order to maximize the treatment process. Some of the methods for waste treatment include the following: biological treatments, detoxification with neutral ash, incineration, open burning.

Controlled Dumps

Freduah (2016) stated that the environmental and biological vices that often create pollution are usually taken care of in controlled dumps. In addition, the methane gas released to the surrounding is controlled. Controlling of dumps has minimized incidence of ground and environmental contamination.

Figure 2: Controlled Dumps by Freduah (2016)

Waste Packaging

Amusan et al. (2013) noted that before disposal and treatment, wastes need to be well packaged. There are containers and bags that are used in refuse and garbage packaging. There are other types of packaging materials that could also be used such as plastic materials, steel bin, plastic bin, steel bins, polythene bags, and aluminum foils among others. Nott considering the type used, cost, quality, aesthetics and durability are desirable qualities in the choice of bins type. Some of the packages take care of emission of poisonous gases such as Methane, Ammonia that could be injurious to health.

Recycling of Waste Disposal

Amusan (2013) and Abdul (2010) were of the opinion that, recycling of waste and garbage are described as a process of converting waste collected into usable items. It is known as converting waste to wealth. Recycling of items is made up of three stages which include the sourcing stage, sorting stage and processing stage. Materials gotten from different locations dumped waste are sorted out according to their categories. Waste are classified into the following classes such as medical waste, animal waste, chemical waste, metallic waste, gaseous waste, biodegradable and non-biodegradable waste and among others. Figure 2.2 shows waste bin collection systems.

Figure 3: Recycling Bins for Waste collection by Amusan (2013)

Vehicle Routing Problem (VRP) Versus Traveling Salesman Problem (TSP)

Vehicle Routing Problem (VRP)

Oxford Dictionary, (2015) defined route as a way or course that exists between a starting point and a destination, which can be transverse". Route is established or feasible path between two nodes or points, from its starting

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point to its destination, or from point of departure to point of termination. Furthermore, Merriam Webster dictionary defined route as, a means to move from one place to another, a way that someone or something travels along regularly.

From the above definitions, two things are vital;

1. Starting point and destination

2. Valid path, which allows movement.

When an existing path between two points (source and terminal) do not allow for movement between the two points (no matter how short that path appears to be), it is not a valid path and hence it is not a route.

Wei-Cheng, (2014) said that vehicle routing problem generally is defined as a series of delivery point and/or receiving point, selecting the proper route with certain constraints orderly through them". Ramser and Dantzig (2014) brought in the idea of formulation of mathematical encoding using approach involving algorithms in solving problems associated with gasoline delivery to stations. Karskens (2015) stated that this problem traced back to the fifties of the past century and it is known as Vehicle Routing Problem (VRP). Today, VRP has drawn the attention of much wide collection of mathematicians, professionals of different disciplines and researchers to this area of study. Caric (2018) opined that the VRP definition states that k vehicles originally positioned at a repository are to distribute distinct number of commodities to w clients. Finding the best route (optimal) to use in meeting the demands of clients by a collection of vehicles is termed as a VRP. The reason is to minimize the general moving costs. The classical VRP problem solution is a set of different routes which all started and stopped in the repository, and which satisfy the restriction with the intention of all the clients being supplied once only. The cost of transportation is improved by reducing the whole travelled space and by dropping the vehicle quantities needed. There are many variance of VRP which are; vehicle routing problem with split deliveries (VRPSD) where each one client will be supplied by several vehicles, vehicle routing problem with time window (VRPTW) focuses on restriction in timing, capacitated vehicle routing problem (CVRP) talks about carrying capacity of the vehicle and vehicle routing problem with time windows and split deliveries (VRPTWSD) is a combination of VRPTW and VRPSD.

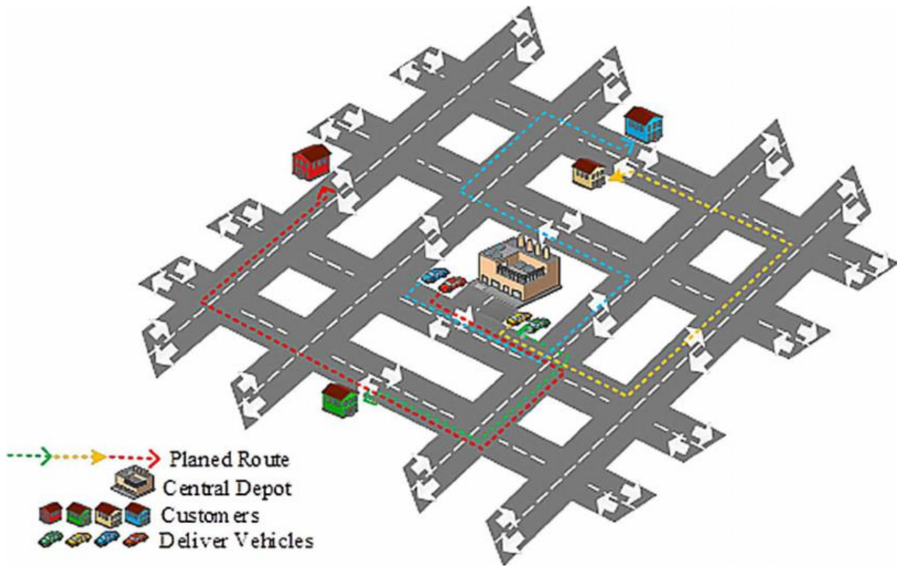

Figure 4: Vehicle Routing Problem (VRP) by Caric (2018)

Travelling Salesman Problem (TSP)

Weinstein, (2015) opined that the traveling salesman problem is made up of a number of cities and a sales representative. The sales representative is needed to visit the cities one after another starting with one of the cities (for instance, the hometown) and arriving back to the city of departure. The problem faced with the travelling salesperson desired is to minimize the total distance of the journey thereby minimizing cost. Karskens

(2015) described traveling salesman problem (TSP) as a combinatorial optimization problem, which studied widely, since the problem appears to be simple but extremely hard to find solution hence attracting scientists and researchers' interest. The purpose of this is to get an optimal route with the motive of traversing through every node at least once in the graph. It has the objective of entirely reducing the travelling span. There is totally no known best method of solving this problem, which now makes it to be an NP-hard (Nondeterministic Polynomial-time hard) problem. The mail delivery problem is same as the VRP where the mail carrier deliver mails to several points and find the routes with less cost and time between the points. The shortest path problem looks at the shortest distance between a starting point and a destination among several alternatives routes.

TECHNIQUES ADOPTED

Dijkstra Algorithm

Bale et al. (2016) said that Dijkstra Algorithm is the main algorithm used in determining the best path". Dijkstra computes the shortest paths between nodes in a weighted graph thereby keep all other provisional distances for every node. Geisberger, (2011) stated that the nodes or points are visited orderly starting from the source to the terminal point in order to achieve the shortest-path. After all the nodes are visited one after the other, the process is ended and it only takes care of single-source problem and also suitable for positive edge weights only.

A* search Algorithm

Bale et al. (2016) said that A* search algorithm is a search algorithm as the name implies which is good in evolving or going round the graph to discover paths. This is the way of finding best or possible path with multiple nodes. Geisberger (2011) opined that A* uses mental shortcuts in solving its problem in order to improve time performance. In order to maintain proper use of time frame, edges are used on targeting the distance so as to facilitate the searching of the algorithm to the desired target. The need of the nodes located in the graph is been resolved based on the temporal distance between the source and terminal including the edge. The productiveness of this technique depends on the edges. Wilkie et al. (2012) pointed out that the poor performance of algorithm is as a result of nodes geographic coordinates making use of the simplest edge in road networks.

ALT **(A* search Landmarks and Triangle inequality)**

ALT is a Dijkstra algorithm that is known for fastness in calculating the shortest paths in road networks that are of large quantities. The ALT algorithm chooses a subset of NP-hard landmarks which performs a particular function with the existence of effectual and no specific answer. A* search Landmarks and Triangle inequality (ALT) algorithm is the breakdown of Dijkstra algorithm that makes use of a π function to assess distances from one node to another in the graph. According to Goldberg, (2015), using landmarks is the same as describe a potential function". Fuchs, (2010) said that "the distances ranging from the starting point to the end of the node are computed through the pre-processing phase, and the triangle inequality is used in approximation of distances within the graph. The triangle inequality is represented using the distance (d) of i, j, k to specify the three different nodes in the graph. That is to say; d(i j) + d(i k) + d(k j), where d(i j) is assumed to be the distance between i and j which is the shortest path between the two nodes length.

Arc Flags

Baum, (2011) added that as the name implies, arc-flags is an additional provided signposts in a graph. The way signposts give human beings direction on a part to follow, is the same role arc-flags perform in enabling Dijkstra algorithm to ascertain the shortest path. Vector of flags are included in each edge of the graph which provides all needed information on whether the same edge possibly leads to the target region or not. This technique helps the Dijkstra algorithm in ensuring that only regions in mind are visited.

METHODOLOGY ADOPTED

Ait Ben Mouh et al. (2023) in their work, showed how prototyping hybrid algorithms is the safest and most cost-effective way to validate route optimization models in logistics. In this paper, prototyping methodology is used

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because it allows rapid testing of algorithms like Dijkstra or A on real-world data before full deployment, reducing risks, saving costs, and ensuring solutions adapt to dynamic traffic and logistics conditions. It provides a practical way to validate theoretical models against actual performance.

The six (6) stages in prototyping methodology

Requirement gathering

The product requirements are brought together and also involves both the developer and customer meeting to know the whole objectives of the software, as well as identify those requirements that are known. They establish some objectives like what the prototype will be used for, and features the final system the prototype would reflect.

i. **Quick design**

This design system is developed the time requirements are known. This involves aspects of the system only that are vital to the construction of the prototype such as the input and output format of software that are known to the user instead of the detailed design plan, which helps to construct a prototype.

Prototype building

This is a model that its information got during quick design is used to develop the software requirements in order to achieve customer satisfaction. It is necessary to ensure low development cost for the prototype, as well as speedy development. This was achieved by disregarding the requirements that are not of interest to the customer.

User Evaluation

The prototype was evaluated in order to identify features that are to be included or removed in the development process of the software. Here, the user expresses how he or she feels about the work to the software developer.

Refining prototype

In this type of prototype, an improvement is carried out on the software, thereby producing a new prototype once the user shows dissatisfaction with the present prototype. There is continuation of evaluation on the new prototype, which the process continues until all necessary requirements are met.

Engineer product

Once the whole requirements are met, the user accepts the end product of the prototype, and evaluates the end system with its regular maintenance in order to prevent its failures.

ANALYSIS OF THE SYSTEM

When we use the term route optimization, we mean solving vehicle routing problems (VRP) and traveling sales representative problems (TSP). It is used in solving different vehicle routing problems such as the capacitated VRP with time windows or the VRP with multiple depots.

The criterion used in determining the best path can be different. This criterion could be distance or travel time. Anything is possible as long as it identified by allocating some quantity, a cost, to each road segment, and looking for the least-cost path. Optimal routes mean the drivers spend less time driving, which reduces fuel costs and can increase the number of stops a driver can make in a day, which can help improve service delivery. The flowchart diagram in Figure 3.2 below illustrates this process.

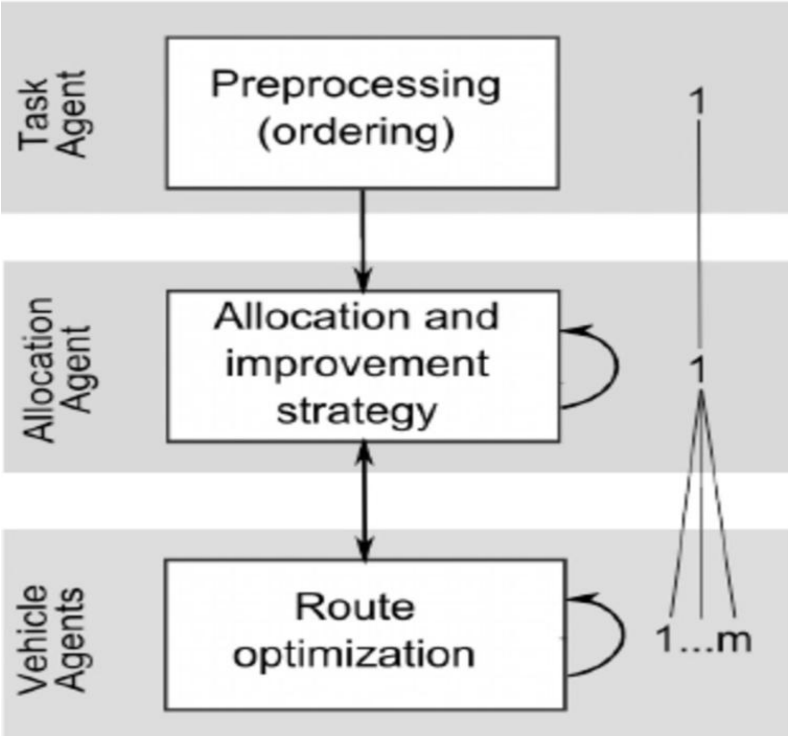

Figure 5: Architecture of existing Route Optimizer by Vokřínek et al.(2019)

CONCLUSION

The method based on route optimization using Dijkstra algorithm to find the shortest path to all other vertices in a graph is applied in considering environmental and economic aspects. Waste disposal management is the process whereby wastes are collected, transported and disposed of in the best possible way of limiting or eliminating the harmful effect of wastes. This aspect of environmental management is of the same importance as other public amenities or infrastructures which without it, the life of people would be extremely difficult. It comes with a lot of cost in terms of fuel cost and distance covered. Many waste bins are scattered across cities with few vehicles to evacuate the waste. Most times vehicles dispatched to collect waste without prior knowledge of the best route to follow for optimal performance. This study uncovers the real nature of road transport and different routing problems in road transportation.

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