# Dynacargo routing subsystem and its algorithms for efficient urban waste collection

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**Abstract** Dynacargo research project aims at developing a near real-time monitoring system that monitors and transmits waste bins fill level, which are used to predict the fill-level of waste bins and dynamically manage the waste collection process by introducing truck distance minimization, relying on efficient routing algorithms. Dynacargo places a set of durable, low cost sensors and RFID tags on waste bins. These tags store the fill-level estimated by the sensors, which is passed through diverse communication channels and ends to a central cargo information management system. Along with this real time data harvesting, data mining techniques are utilized on historical data collected prior to Dynagargo implementation, in order to predict future waste bins fill rates. In this paper we focus and present the research issues that have emerged along with the design and development of the Dynacargo routing subsystem and its algorithms.

**Keywords** routing algorithms · system architectures · data mining · urban solid waste collection

## 1 Introduction

Nafpaktia municipality is a typical case of solid waste management throughout Hellas, as waste collection is based on standard time intervals and according to fixed vehicle routes. Decision making is solely empirical, which leads to biased

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decisions that do not take into account real needs based on data. This has led to results far from optimal; as it is not uncommon to have overfilled waste bins were uncollected for some days, while at the same time other unfilled bins were collected, resulting to an unsatisfied local society along with increased cost. Regarding Athens [8], it has been estimated that the 60% to 80% of the total cost of waste collection, transportation and disposal is spent during collection. The main cost reduction efforts should deal with distance and duration minimization of vehicle routes [6]. Johansson [7] proved that if the fill level of bins was taken into account and waste collection adapts accordingly, it could reduce the cost of waste collection up to 20%. Under the light of these findings, Dynacargo (Dynamic Cargo Routing on-the-Go) project attempts to build a near real-time monitoring system that monitors and transmits waste bins fill level, in order to make waste collection more efficient by cost reduction which is accomplished by minimizing distances covered by refuse vehicles. In this paper we focus on the Dynacargo routing subsystem. We discuss in detail the research issues that have emerged during the design and development of the routing algorithms, we present our algorithmic approaches and we illustrate the promising evaluation results.

## 2 Related Work & Innovation of Dynacargo

There are various approaches available in order to harvest data from points of waste collection [2–5, 7, 9, 10]. Although they introduce interesting approaches, they cannot be used as-is in Dynacargo. This is because they introduce major costs, they do not meet Dynacargo functional requirements and are mostly customized for recyclable waste which can be managed with longer collection cycles compared to domestic waste.

This implies that Dynacargo, despite aiming at waste collection automation as existing approaches do, displays major differentiations against these approaches. At the heart of these differentiations lies Dynacargo architecture which originates from a generic multipurpose cargo-based dynamic vehicle routing approach which copes with cargo changes and collection from disperse points of concentration. Dynacargo moves forward from sole data collection from waste concentration points, as it utilizes such data in real time in order to optimize vehicle routes during the waste collection process execution.

Another point at which Dynacargo differentiates from existing approaches is the utilization of a diverse set of data transmission techniques that is incorporated to establish data transmission from points of collection to the system in near real time. Besides GSM which induces fixed telecom costs, Delay-Tolerant Networking concepts are adapted for data transmission from the disperse concentration points to the central information system. Dynacargo DTN is based on a set of existing public commuters that are utilized as data hosts that carry data as they execute unaltered standard procedures.


Fig. 1: Indicative waste collection routes for Nafpaktia.

## 3 Dynacargo project overview

Dynacargo functional requirements evolved from the analysis of the solid waste collection and management system of Municipality of Nafpaktia, Greece, which expands in an area of 870.38 $km^2$ and displays a population of 27,800 citizens. Nafpaktia displays geographic and demographic aspects that sum to an ideal pilot environment for Dynacargo. It is composed from a coastal city with narrow busy streets in the historic center, coastal towns and villages with population varying following tourist seasonality, along with remote villages (up to 120 km away) with a few dozen residents located in mountainous areas. Another diversion is that Nafpaktia displays waste transshipment from small to big refuse vehicles. Requirement analysis initiated with an as-is analysis in order to formally document the current waste management process. Several indicative waste collecting routes were selected and modeled on Google Earth (Figure 1), after an assessment of peculiarities each route presents. The analysis included available waste collection historical data and information regarding related processes.

In order to reassure the accurate Dynacargo waste level predictions, waste bin fill level data is acquired at short time intervals from as many as possible waste collection points. Data collection is realized through diverse data harvesting tools take advantage of existing transportation systems such as public bus services, postal office vehicles, taxis, municipal police vehicles, along with active social entities as these vehicles traverse the area of interest in an irregular but frequent manner. The Data Collector role can be served by either a vehicle driver (e.g., bus, taxi, postman car, etc.) equipped with the Dynacargo equipment, or anyone else who may be involved in data collection (e.g., postmen) who may use any means of transportation such a car, a bike, or by foot. Citizens improve data harvesting by reporting fill-level with a mobile application, reporting estimations of produced waste volume on unforeseen events and by checking online the bin fill levels near their residence so as to discard their waste on nearby unfilled bins.

The functional requirements and the Dynacargo architecture are described in detail in our previous research works [1,14]. Dynacargo architecture is designed as a generic cargo-based routing system along with the inherited adaptability to any other municipality regardless of specific waste collecting process characteristics. In the context of this paper, the most important architectural parts are:

**Central System** It is the back-end system of Dynacargo. Its main part is the Data Warehouse storing all historic data, bins fill level transferred by the collectors, vehicles data and everything needed for calculating the best routes based on the current load of bins and some restrictions (Bin Collection Settings) specified by the system administrators. Moreover, Data Warehouse stores any information derived from other subsystems, particularly from the Data Mining Subsystem and the Routing Optimization Subsystem.

**Data Mining and Prediction Subsyste**m Its role is to analyze the current and historic data and predict the fill level of the bins, especially when we do not have the available information updated or is not fairly recent, based on the day, month and region where the waste bin is located.

**Routing Optimization Subsystem** The role of this subsystem is the dynamic route planning before the starting of truck routes, and the on-the-fly modification of routes, either due to exceptional events (accident), or if the new data collected during the routes impose such changes.

This work is focused on the design of the last module and its algorithmic approaches, which are presented in the following sections.

## 4 Problem model

In our formulation, the Urban Waste Collection Problem (UWCP) can be described as follows. Let a set of geospatial points $N = 1, 2, ..., n$ define the waste bin locations. Let a set of 3 dimensional geospatial points $D = 0, n+1, n+2...n+2v$ define the possible start and finish geospatial points for the refuse vehicles. Let $G = (N \cup D, A)$ be a directed graph where $N \cup D$ is the set of nodes and $A$ is the set of arcs, $A = \{(i, j) : i, j \in N \cup D, i \neq j\}$ where each arc represent a feasible direct connection between nodes. Each edge $A_{ij}$ has a set of properties, like distance $td_{ij}$, travel time $tt_{ij}$, slope $sl_{ij}$, minimum road width $mrw_{ij}$, etc. For each pair of nodes within a cluster, there exist two arcs, one for each direction as some properties like the actual distance, travel time between them is calculated considering traffic restrictions like one way streets and restricted turns.

Each waste bin $B_k$ is associated with a set of properties like geospatial point $N_i$, an identifier $b_k$, type $bt_k$, capacity $bc_k$ and average daily volume growth rate in winter $bagw_k$ and summer $bags_k$. In addition, a number of "instance" properties is associated with each bin effecting the properties of generated solutions. Day Limit $bdl_k$ defines the maximum time period, in days, that a bin can remain uncollected. This property depend on the seasonal period and the location of the bin. Upper limit $bul_k$ defines the fill-level percentage that makes the collection obligatory. Lower limit $bll_k$ defines the fill-level percentage that makes the collection unnecessary. Finally, waste average weight per liter $bvwr_k$ defines the current rate between waste volume and weight ratio as the vehicles have their capacity as weight and the bins expose their fill rate as volume. This property also changes during different year periods and locations, depending on the activities in the area.

In addition, the bins can be clustered given different criteria like belonging area and bin type. We define a problem group $G_m$ as a bins cluster that is serviced by a subset of vehicles. Most non-urban municipalities, especially in Greece due to the land structure, include geographically scattered villages or towns, thus in our model we group the bins of a village or a suburb into bin clusters. This helps the problem solution as it is usually more economically viable to collect all bins in a village than returning the following day to partially collect them. We define a bin cluster $C_n$, as the set of bins belonging to a certain disjoint area and for each bin cluster we set up to three entry / exit points for a typical village or town. By using the entry / exit points of all bin clusters, the landfill location and the vehicle starting and ending points, we can construct a significantly smaller graph, vastly accelerating the performance of the routing algorithms. For each pair of nodes in this graph, the actual distance between them is calculated considering traffic restrictions, in both directions.

The vehicles set $V = 1...v$ represents the refuse vehicles. For each vehicle a set of properties like registration number $vid_l$, capacity $vc_l$, average fuel consumption $vfc_l$, start $vs_l$ and finish $vf_l$ points, and servicing bin types $vbt_l$ and area. Each truck must unload the collected waste before returning to the finish point. Thus each truck route must either transship the collected waste to another vehicle or pass from the landfill and then move directly to the finish point without servicing other bins. The problem goal consists of finding minimum total cost tours of the available vehicles starting and ending at their respective start and end points, such that each bin should be visited at most by one vehicle and the load of each vehicle does not exceed its capacity. For each vehicle, we also have impose a use cost in order to promote the use of fewer vehicles if possible. For each vehicle, the cost for each arc is a function of the travel distance of the arc, the average fuel consumption of the vehicle and the cumulative collected weight of the sub-tour from the start node until the current arc.

The problem can be categorized as a Generalized Vehicle Routing Problem and an ILP model formulation can be found in [15].

## 5 Model Parameters Estimation

For each bin, a current state estimation using multiple information streams is implemented. Each information stream is a time series that depict the behavior of each bin. In the current implementation we support the following information streams:

- Independent Collectors that register the bin id, a timestamp and the bin fill-level percentage. This information is collected several times daily by various collectors passing by the bin, carrying a Bins Data Gathering Subsystem.
- The DataMining Subsystem that register the bin id, a timestamp for the prediction, the forecasted bin fill-level percentage and the forecasted waste weight.
- Refuse track that register the bin id, the actual bin fill-level percentage, the collected waste weight and the days passed since the last time the bin was emptied.

The estimation process is executed before each routing algorithm execution and the waste volume and weight properties included in each bin are set. The average daily volume growth rate per period is used by the routing algorithms to create finer priority levels between similar half-filled bins. The average daily volume growth rate will be calculated with great accuracy the more the system becomes fully operational. In the context of the project, we tried to estimate those values based on the empirical assessment of drivers for the average occupancy rate for each bin depending on the season.

## 6 Nafpaktos Instance

The studied instance of Nafpaktos municipality has 2,100 bins partitioned in 2 bin types, small (240lt) and large (1,100lt) ones. There exist 11 refuse trucks belonging to 6 different kinds with diverse characteristics including capacity (from 1.5m$^3$ to 9m$^3$), fuel consumption and servicing bin types. In addition, there is a single small truck that can service bins in the historic center of Nafpaktos, a limitation imposed due to narrow roads. This small truck can also be used to collect small bins outside the historic center. In practice, this vehicle is the preferred method of collecting small bins located in the suburbs mainly due to lower fuel consumption. The disadvantage is that the small truck cannot go to the landfill and thus has to transship its waste cargo to a larger refuse truck. We have grouped bins and vehicles into two solution groups, regarding which types of bins are services by the vehicles.

- **Group 1**. In the first group, we associate the small truck and all small bins.

– **Group 2**. In the second group, we associate the rest of the vehicles and all large bins, plus those small bins that are not located in narrow roads.

Table 1: Generic Region Types

| Region Type ID | General description | Regions of Nafpaktia |
|---|---|---|
| 1 | Historic Center | Historic center of Nafpaktos city (around the castle) |
| 2 | City | City of Nafpaktos (densely populated areas with blocks of flats) |
| 3 | Suburb | Suburb area of Nafpaktos city (mainly houses and small apartment buildings) |
| 4 | Town | Antirrion |
| 5 | Village – Rural area | Routes to Panw Neokastro, Paleochoraki and St Ioanni monastery |
| 6 | Remote area | Route of Apodotia |

Moreover, we have separated the bins in the following bins clusters due to geographical constraints (geographically scattered villages or towns) or bins type within cities.

– **Cluster A** (Central part of Nafpaktos) – red route in Fig. 1
– **Cluster B** (West part of Nafpaktos) – purple route in Fig. 1
– **Cluster C1** (East part of Nafpaktos) – orange route in Fig. 1 (plain)
– **Cluster C2** (Pano Neokastro) – orange route in Fig. 1 (mountain)
– **Cluster D** (Paliochoraki) – lime route in Fig. 1
– **Cluster E** (St. Yannis) – yellow route in Fig. 1
– **Cluster F** (Antirrion) – green route in Fig. 1
– **Cluster G** (Apodotia) – blue route in Fig. 1

At first, we classified all bins according to the type of their geographic region, in order to be able to analyze historic data (plus future data) and facilitate administrators to configure the routing subsystem. The categories we chose are general and can be applied to any municipality. They are outlined in Table 1.

The dynamic data as estimated for the municipality of Nafpaktia are shown in Table 2. These values can be modified by the administrator whenever necessary. Figure 2 shows the different daily growth rates of bins occupancy per geographic region and seasonal period.

## 7 Algorithmic Approaches

The UWCP can be classified is a variant of the Generalized Vehicle Routing Problem (GVRP) where the approach methods are grouped into the following categories [11]: Branch-and-Bound, Branch-and-Cut (hybrid methods between Branch-and-Bound and Cutting Plane methods), Set-covering based

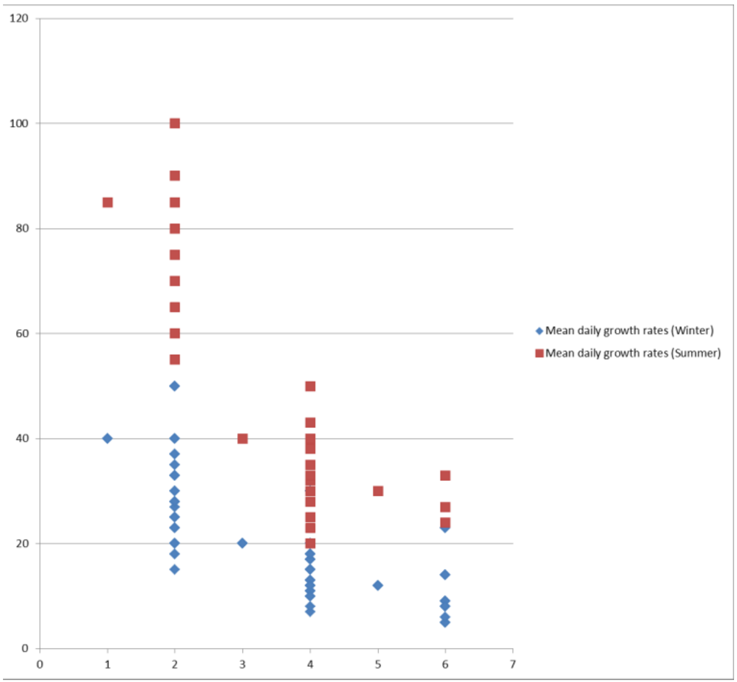


Fig. 2: Daily growth rates of bins fill levels per geographic region and seasonal period.

Table 2: Administrator's Dynamic Data for Nafpaktia

| Region Type ID | Waste average weight (kg) per lt | Lower limit (% volume) | Upper Limit (% volume) | Day Limit (winter) | Day Limit (summer) |
|---|---|---|---|---|---|
| 1 | 0.10 | 20 | 60 | 3 | 2 |
| 2 | 0.10 | 20 | 60 | 3 | 2 |
| 3 | 0.09 | 20 | 70 | 5 | 3 |
| 4 | 0.08 | 20 | 70 | 5 | 3 |
| 5 | 0.07 | 20 | 75 | 7 | 4 |
| 6 | 0.06 | 20 | 80 | 7 | 4 |

algorithms, Heuristics and Metaheuristics. Alternatively, the UWCP can be approached as a Capacitated Team Orienteering Problem (CTOP) [12]. The orienteering problem is a combination of vertex selection and determining the shortest Hamiltonian path between the selected vertices. The OPs goal is to maximize the total score collected, while the GVRP only tries to minimize the travel time or distance, while covering all vertices. On the other hand in the OP not all vertices have to be visited. Based on the above observation, we have created two heuristic approaches that use the GVRP and CTOP as subproblem solvers after some preprocessing steps.

### 7.1 Preprocessing

*Step 1: Calculate bins priority.* Based on bins dynamic data and the current seasonal period, for each Bk a priority is calculated, based on the days passed since last collection and fill-level forecast. The algorithm that calculates the priority for each bin can be parameterized by system administrators and is described below:

- If we have reached the day limit since bins last collection, then Priority = 4
- If forecasted value of the bin fill-level ≥ Upper Limit, then Priority = 3
- If Lower Limit ≤ Forecasted value of the bin fill-level < Upper Limit, then Priority = 2
- If forecasted value of the bin fill-level < Lower Limit, then Priority = 1

*Step 2: Bin clusters inclusion.* For each suburban bin cluster $C_n$, check whether or not to be collected as a whole. A positive decision is realized if any of following criteria stands:

- The priority of one bin in the cluster is 4.
- The priority of at least 50% (this value may vary among clusters) of bins in the cluster is 3.
- The total waste of the bins in the cluster exceeds a certain threshold. This threshold can be configured per cluster. The purpose of this threshold is to prevent uncontrolled growth of the waste volume, in order to prevent us to send larger trucks which usually impose high fuel consumption.

### 7.2 Dynacargo Routing Algorithm – CVRP subproblems

*Step 1: Calculate for each Gm with delivery a CVRP solution.*

- Solve a CVRP routing problem for all bins in the group with priority 4 and 3.
- Solve a CVRP routing problem for each suburban cluster, included in preprocessing step 2, including all bins that belong to the cluster.
- Set the load to zero for all bins that belong to vehicle routes.
- Assign the total load of each vehicle route to the last bin in its route, and set priority 4 for this bin. We consider this bin as the location of the waste transship.

*Step 2: Calculate a solution for all other $G_m$ not solved.*

- Include all nodes with priorities 4 & 3, thus all transship bins locations.
- Solve incrementally the routing problem for the remaining clusters by choosing the most appropriate vehicles (by taking capacity and fuel consumption under consideration)
- The solution will be comprised by the routes assigned to all used vehicles.

*Step 3: Add Bins with priority 2.* In this step, the algorithm selects the vehicle with the least capacity required by the load of each route. If there is available capacity in one (or some) vehicles, choose some extra bins with priority 2 in order to add to the vehicle's route, using the following criteria:

- Choose those bins that elongates less the existing route.
- Choose those bins that their next day priority will be 3 or 4 (ie. jf current cargo volume + daily growth $\geq$ upper limit or if tomorrow we reach the day limit of the bins).

*Step 4: Simulate Run per depth of d days.* In order to estimate the quality of the generated solution, we perform the following steps for the next week:

- Only for bins that belong to solution: Reset the load of bins and set field DaysFromCollection to zero (0).
- For all bins: Calculate bins load for the next day, by adding the current load of the bin plus the value of field AvgPerc field. Then increase by one the field DaysFromCollection.
- Solve next day (steps 1-3).

At the end calculated the number of routes, total kilometers and fuel consumption for the whole week.

### 7.3 Dynacargo Routing Algorithm – CTOP subproblems

The second approach is to model the problem as a Capacitated Team Orienteering Problem (CTOP). In the CTOP formulation of the problem, we model each bin to have a demand and a profit. The goal of the algorithm is to maximize the collected profit collected, while satisfying vehicle capacity constraints. In our approach, we model the demand to be weight of that each bin holds and the profit as a function of the priority of the bin, the current and the forecasted next day fill level. The approach tries to maximize the collected garbage given that each vehicle has a maximum capacity and the need to minimize the cost per kilogram of collected waste. In this approach, we include all the available bins and the algorithm decides if any additional bins besides the high priority ones, should be collected. In the context of the project the following approach was selected:

*Step 1: Solve subproblems with delivery.* We solve each subproblem that will not directly deliver the waste to the sanitary landfill but the utilized vehicles will reload midway the collected waste to other vehicles. This may be required as we can use lower vehicle costs for accessing the sanitary landfill which is usually at a remote location from the municipal center. For each subproblem, we take into account all available bins and we solve a CTOP problem setting the start point of every vehicle their current position and as the end point the possible delivery spots. After solving each delivery subproblem, we create virtual bins at possible delivery points, where each bin has the total collected capacity from each vehicle and we introduce a constraint that exactly one virtual bin per delivered waste should be collected. In this way, we make sure that the delivery will be performed and the delivered waste will not be used more than once.

*Step 2: Solve the remaining bin clusters.* In the second step, we use the virtual bins from the delivery subproblems along the rest of the bins. We solve a CTOP problem setting the start point of each vehicle their current position, the end point the vehicle garage and as a constraint that if a vehicle is loaded, it should pass from the sanitary field before returning to the garage in order to unload collected waste. We use a logarithmic profit function that uses the priority of the bins and in all our test cases the high priority bins were collected while low priority bins are only collected if the bins are almost in the direct path of the vehicle and there is surplus capacity in the used vehicles.

*Step 3: Simulate Run per depth of d days.* In order to estimate the quality of the generated solution we also solve a sequence of instances for the next d days using forecasted data. We generate solutions and evaluate if the average cost per collected waste for the sequence horizon increases. If this happens, we adjust the search parameters as this is an indication that the currently generated solution leaves waste to the uncollected bins that will create demand in the following days that will increase the total cost.

## 7.4 Operational Solution Selection and Dynamic Routing

As there could be other constraints like the availability of crew personnel, special waste collection needs, maintenance requirements etc that are currently not captured in the optimization model, more than one solution is generated by calling the routing algorithms with different parameters and the system operator manually selects the one that will be operated. Both algorithmic approaches are executed every time a new solution is required and each approach may produce a set of possible solutions. The system operator can then compare them and select the best one. The predominant approach is to use the ratio of weekly kilometers and fuel consumption per ton of waste collected as the selection criteria.

During the operation of the planned operation, a dynamic re-routing algorithm is performed to adjust the planned solution to updated data. The algorithms are centrally executed and the updated route are transmitted to the on truck onboard device. To perform dynamic routing we implement the following strategies:

- At the Bin layer:
  - As the system is fed in real time about bin fill levels, the executed routes are enriched by those bins with priority 2 or 1 which are located on the route, although they were not selected by the algorithm. These bins will be collected by the refuse truck, only if their fill-level exceeds

the upper volume limit of each bin. Drivers are informed in real time as they approach such a bin and notified in time if they have to stop to collect it.
- At the route layer:
  - As the bins are collected by the refuse truck, the truck system calculates the total difference between the actual wastes in bins with the predicted values. If the collected waste is more than the predicted one, priority 2 bins included in the planned route are removed, starting from the ones near the end of the route.
- Re-routing:
  - When a vehicle is unable to continue its route, we then resolve the problem using the partial operated routes and vehicle state as fixed partial solutions. More specifically we use:
    1. The current positions of all other vehicles.
    2. Their current available capacities.
    3. The current routes that they have planned to operate
    4. Forecasts of bins that have not yet been collected, now taking into account only priority 3 & 4 bins.

## 8 Implementation and Evaluation

For the studied problem, the actual distance between two geographic points is calculated by using the QGIS tool and the Open Street Map platform via the online routing API that is provided. Our internal representation are based on the open standards WGS84 coordinate system, enabling us to easily extend it to use the routing API of Google or Bing Maps in the future. We used OR-tools [13] as the underline solver infrustrucutre, more specifically the routing constraint solver. The heuristic approach is implemented in Python and uses a callable CVRP model that can use multiple depots for each subproblem. The CTOP approach is implemented in Java and directly models the problem as a constraint programming problem.

At first routing data was calculated (number, distance, fuel consumption, garbage load) for the current garbage collection process for the selected routes. Table 3 presents for each route:

- **ML**: Mean load per route in kilograms
- **Freq**: the route frequency per week (for example there are 4 routes per week for Antirrion thus the frequency is 7/4 = 1.75)
- **Km**: Kilometers of each route.
- **Km (year)**: Kilometers of each route per year.
- Total mean kilometers per year and week.

Table 4 illustrates per route and season (winter – summer):

- Number of routes executed every 7 days
- Number of kilometers every 7 days
- Number of fuel liters every 7 days

Table 3: Routing data.

| Fixed Routes | Oct to Mar ML | Oct to Mar Freq. | Apr to Sep ML | Apr to Sep Freq. | km | km (year) |
|---|---|---|---|---|---|---|
| F (Antirrion) | 3900 | 1.75 | 5400 | 1.75 | 79 | **16432** |
| G (Apodotia) | 3800 | 7 | 3200 | 7 | 290.5 | **15106** |
| A (Central part of Nafpaktos) | 4400 | 1 | 5500 | 1 | 50.8 | **18491** |
| B (West part of Nafpaktos) | 300 | 1.17 | 500 | 1.17 | 30.6 | **9547** |
| C (East part of Nafpaktos) | 800 | 7 | 700 | 7 | 87 | **4524** |
| D (Paliochoraki) | 200 | 7 | 170 | 7 | 22 | **1144** |
| E (St. Yannis) | 100 | 7 | 80 | 7 | 35 | **1820** |
| | | | | | TOTAL Km | **67064** |
| | | | | | Km / week | **1290** |

Table 4: Seasonal routing data.

| | Routes W | Routes S | km W | km S | fuel (lt) W | fuel (lt) S |
|---|---|---|---|---|---|---|
| F (Antirrion) | 4 | 4 | 316 | 316 | 161.16 | 161.16 |
| G (Apodotia) | 1 | 1 | 290.5 | 290.5 | 81.34 | 81.34 |
| A (Central part) | 7 | 7 | 355.6 | 355.6 | 209.80 | 209.80 |
| B (West part) | 6 | 6 | 183.6 | 183.6 | 22.03 | 22.03 |
| C (East part) | 1 | 1 | 87 | 87 | 46.98 | 46.98 |
| D (Paliochoraki) | 1 | 1 | 22 | 22 | 2.64 | 2.64 |
| E (St. Yannis) | 1 | 1 | 35 | 35 | 4.20 | 4.20 |
| | **21** | **21** | **1289.7** | **1289.7** | **528.16** | **528.16** |

| | Load 7 days W | Load 7 days S | Load 1 day W | Load 1 day S |
|---|---|---|---|---|
| F (Antirrion) | 15,600 | 21,600 | 2,228.57 | 3,085.71 |
| G (Apodotia) | 3,800 | 3,200 | 542.86 | 457.14 |
| A (Central part) | 30,800 | 38,500 | 4,400.00 | 5,500.00 |
| B (West part) | 1,800 | 3,000 | 257.14 | 428.57 |
| C (East part) | 800 | 700 | 114.29 | 100.00 |
| D (Paliochoraki) | 200 | 170 | 28.57 | 24.29 |
| E (St. Yannis) | 100 | 80 | 14.29 | 11.43 |
| | **53,100** | **67,250** | **7,585.71** | **9,607.14** |

– Collected waste load in kilograms every 7 days
– Collected waste load per route and day

Table 5 illustrates per season (winter – summer):

– Number of routes executed every 7 days for 6 months and for an entire year.
– Collected load in kilograms every 7 days for 6 months and for an entire year.
– Number of kilometers every 7 days for 6 months and for an entire year.
– Liters of fuel every 7 days for 6 months and for an entire year.

In order to assess algorithm efficiency Dynacargo operation was simulated for one year (2013). We built software to produce virtual loads per bin based on real data, like the total load weight per route throughout the year and the empirical estimations of drivers per bin. The result of this procedure was a set of predictions regarding bin fill levels for 10 days of the year (1st and 15th

Table 5: Summary of seasonal routing data (winter – summer).

| Routes | | Waste (kg) | | Km | | Fuel (lt) | |
|---|---|---|---|---|---|---|---|
| W | S | W | S | W | S | W | S |
| 7d | 7d | 7d | 7d | 7d | 7d | 7d | 7d |
| 21 | 21 | 53,100 | 67,250 | 1,289.70 | 1,289.70 | 528.16 | 528.16 |
| 182d | 182d | 182d | 182d | 182d | 182d | 182d | 182d |
| 546 | 546 | 1,380,600 | 1,748,500 | 33,532.20 | 33,532.20 | 13,732.06 | 13,732.06 |
| | **1,092** | | **3,129,100** | | **67,064.40** | | **27,464.11** |

day for some summer and winter months of 2013) which were produced by the prediction subsystem.

Afterwards the routing algorithm was executed for these 10 days and number of routes, kilometers and fuel was calculated for each week. The level of vehicle fill was calculated by dividing the actual weight of collected garbage during each week by the total vehicle load capability. These results are displayed and compared with corresponding weekly values of current fixed routes in Table 6.

The following improvements were detected:

Winter:

- **Routes**: 13 instead of 21 (38.10% drop)
- **Kilometers**: 946.6 instead of 1,289.7 (26.60% drop)
- **Fuel**: 275.4 instead of 528.16 (47.86% drop)
- **Vehicle fullness**: 86% instead of 53%.

Summer:

- **Routes**: 16 instead of 21 (23.81% drop)
- **Kilometers**: 1,050.4 instead of 1,289.7 (18.55% drop)
- **Fuel**: 314.6 instead of 528.16 (40.43% drop)
- **Vehicle fullness**: 85% instead of 67%.

As Dynacargo can reach a 100% fill level per vehicle instead of 85%, a 15% margin regarding vehicle load was imposed in order to compensate with potential forecast errors regarding bin fill level. An improved vehicle fill level is accomplished because the algorithm selects a vehicle with the required capacity as the load demand of each route is known before the route execution begins. These results when projected to an annual level yield the figures reported in Table 7.

Route analysis per route is displayed in Table 8. For the specific case interesting conclusions can be derived:

- Remote routes which display small loads there is no significant improvement. This happens because a minimum of 1 route per week is executed regardless of load due to the nature of the load (waste cannot left at the bin for more days than a specific threshold).
- Remote routes which display larger loads 1 to 4 routes can be eliminated which is a significant gain.

Table 6: Improvements over fixed routes.

(a) Winter

| | Routes 7 days | km 7 days | fuel (lt) 7 days | Vehicle fullness 7 days |
|---|---|---|---|---|
| | **21** | **1,289.7** | **528.16** | **53%** |
| 1/3/2013 | 13<br>**38.10%** | 949<br>**26.42%** | 290<br>**45.09%** | 81% |
| 1/10/2013 | 13<br>**38.10%** | 938<br>**27.27%** | 262<br>**50.39%** | 82% |
| 15/2/2013 | 14<br>**33.33%** | 974<br>**24.48%** | 287<br>**45.66%** | 90% |
| 15/11/2013 | 12<br>**42.86%** | 914<br>**29.13%** | 267<br>**49.45%** | 90% |
| 15/12/2013 | 13<br>**38.10%** | 958<br>**25.72%** | 271<br>**48.69%** | 87% |
| **Average** | **13** | **946.6** | **275.4** | **86%** |
| **Avg reduction** | **38.10%** | **26.60%** | **47.86%** | |
| **Std dev** | **3.37%** | **1.74%** | **2.35%** | |

(b) Summer

| | Routes 7 days | km 7 days | fuel (lt) 7 days | Vehicle fullness 7 days |
|---|---|---|---|---|
| | **21** | **1,289.7** | **528.16** | **67%** |
| 1/6/2013 | 16<br>**23.81%** | 1,035<br>**19.75%** | 313<br>**40.74%** | 81% |
| 15/6/2013 | 16<br>**23.81%** | 1,032<br>**19.98%** | 306<br>**45.09%** | 85% |
| 1/7/2013 | 16<br>**23.81%** | 1,089<br>**15.56%** | 316<br>**40.17%** | 89% |
| 15/7/2013 | 16<br>**23.81%** | 1,049<br>**18.66%** | 314<br>**40.55%** | 84% |
| 1/9/2013 | 16<br>**23.81%** | 1,047<br>**18.82%** | 324<br>**38.65%** | 85% |
| **Average** | **16** | **1,050.4** | **314.6** | **85%** |
| **Avg reduction** | **23.81%** | **18.55%** | **40.43%** | |
| **Std dev** | **0.00%** | **1.77%** | **1.22%** | |

Table 7: Dynacargo overall improvements over current solution.

| | Routes | km | fuel (lt) |
|---|---|---|---|
| Currently | 1,092 | 67,000 | 27,500 |
| Dynacargo | 754 | 52,000 | 15,400 |
| Reduction | **31%** | **22%** | **44%** |

- Even more significant improvements were displayed by bins in the Nafpaktos area (D3 and D4), which was not expected. Specifically:
  - Route (B) (small vehicle) is executed 3 times during winter instead of 6, and 5 in the summer instead of 6.
  - Route (A) (Nafpaktos center) is executed 3 times instead of 7 in the winter, and about 4 times instead of 6 in th summer.

Table 8: Route Analysis per route.

| | F | G | A | B | C | D | E | **Total** |
|---|---|---|---|---|---|---|---|---|
| 1/3/2013 | 3 | 1 | 3 | 3 | 1 | 1 | 1 | **13** |
| 1/10/2013 | 2 | 1 | 4 | 3 | 1 | 1 | 1 | **13** |
| 15/2/2013 | 3 | 1 | 4 | 3 | 1 | 1 | 1 | **14** |
| 15/11/2013 | 3 | 1 | 2 | 3 | 1 | 1 | 1 | **12** |
| 15/12/2013 | 3 | 1 | 3 | 3 | 1 | 1 | 1 | **13** |
| 1/6/2013 | 3 | 1 | 4 | 5 | 1 | 1 | 1 | **16** |
| 15/6/2013 | 3 | 1 | 4 | 5 | 1 | 1 | 1 | **16** |
| 1/7/2013 | 4 | 1 | 3 | 5 | 1 | 1 | 1 | **16** |
| 15/7/2013 | 3 | 1 | 4 | 5 | 1 | 1 | 1 | **16** |
| 1/9/2013 | 3 | 1 | 4 | 5 | 1 | 1 | 1 | **16** |

The specific municipality has more routes which were not examined during the project which it is expected to display similar improvements when analyzed. Thus we can securely conclude that for all routes in Nafpaktia the improved figures would be:

- 26,000 less kilometers
- 24,000 less liters of fuel

According to accounting conducted by the Municipality of Nafpaktia, each kilometer costs 1.8 €. Thus Dynacargo introduced a total saving of $26,000 \times 1.8€ = 46,800€$ per year.

## 9 Conclusions

Sustainable growth, in regards to urban areas, requires intelligent waste collection management. Dynacargo serves this need by developing a cargo-centric waste transport management system and by implementing a fully functional instance regarding domestic waste collection in a real life large scale scenario.

This is achieved by expanding traditional fleet management functionality in two manners. One breakthrough that Dynacargo utilizes is to stream near real-time waste related information (fill level of waste bins) into the monitoring and decision support process, prior to collection from waste concentration points. If this information is not available or not efficient from a cost-benefit perspective, it is substituted by historical data in order to predict waste bins status. The second breakthrough that Dynacargo introduces is active citizen involvement, by turning them into active information producers and consumers. Dynacargo utilizes low-cost durable RFID tags, along with alternative network protocols such as DTN in order to minimize telecommunication and hardware costs.

But the most important cost reduction is accomplished by minimizing distances covered by refuse trucks. In order to achieve this we have introduced dedicated dynamic routing algorithms specifically created for this kind of problems. In this paper we present these routing algorithms and the methodology we followed in order to design and implement them. Furthermore, we evaluated these algorithms against the currently used fixed routes and the results showed that the improvement could be up to 22% less kilometers and 44% less liters of fuel per year.

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