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A web-based decision support system for waste lube oils collection and recycling ☆

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Abstract

This paper presents a web-based decision support system (DSS) that enables schedulers to tackle reverse supply chain management problems interactively. The focus is on the efficient and effective management of waste lube oils collection and recycling operations. The emphasis is given on the systemic dimensions and modular architecture of the proposed DSS. The latter incorporates intra- and inter-city vehicle routing with real-life operational constraints using shortest path and sophisticated hybrid metaheuristic algorithms. It is also integrated with an Enterprise Resource Planning system allowing the utilization of particular functional modules and the combination with other peripheral planning tools. Furthermore, the proposed DSS provides a framework for on-line monitoring and reporting to all stages of the waste collection processes. The system is developed using a web architecture that enables sharing of information and algorithms among multiple sites, along with wireless telecommunication facilities. The application to an industrial environment showed improved productivity and competitiveness, indicating its applicability on realistic reverse logistical planning problems.

Keywords: Decision support systems; Vehicle routing; Waste management

1. Introduction

This paper reports on a research project with a leading multi-national Greek company in lubricant production and sole in recycling in Greece. The motivation for this research stems from the interrelationship between environmental considerations and benefits of recycling products. We consider waste lube oils (WLO) collection and regeneration as the focal coupling process of environmental consciousness and profitable recycling operations, and propose the appropriate decision making methodologies, management tools and techniques to transform these processes into state-of-the-art seamlessly running systems. The main focus is on the development of a web-based decision support system (DSS) that enables schedulers and decision makers to address reverse logistical planning problems and monitor effectively operations using novel computational methods and Information and Communication Technology (ICT).

The WLO collection and regeneration processes involve the upstream movement of WLO from several sets of collection points through a network of accumulation points to a central regeneration facility, where new lubricants are produced. Accumulation points refer to regionalized intermediate transfer facilities used to accumulate WLO locally. The latter is the major raw material for the production of basic lube oils and new lubricant products, via a continuous multi-stage regeneration. To the other end, the collection needs for WLO (actual production–regeneration requirements) is determined by customers' demand for end-item lubricant products. Therefore, distribution

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of end-items, production scheduling, inventory and WLO collection are all linked in a reverse planning fashion constituting a closed-loop supply chain.

Reverse logistics encompass the activities all the way from used products no longer required by the user to products again usable in market (Fleischmann et al., 1997). Therefore, while logistic activities involve material flow forward through the supply chain, reverse logistics, or similarly closed-loop supply chains, address the return flows from the user and encompass the re-processing into a usable product. There are four basic characteristics, namely the return reasons and driving forces, the type of products, the recovery processes and the actors involved. All these characteristics are interrelated and their combination determines to a large extent, the type of issues arising from the resulting reverse logistics system.

Carter and Ellram (1998), Fleischmann et al. (1997) and Dekker et al. (2003) provide recent surveys on theory building, quantitative modeling and case studies. Beullens (2004) provide an exploratory analysis on several operational and strategic issues penetrating reverse logistics systems. French and LaForge (2006) investigate several re-use issues (returns, re-use options and others) and practices related to process industry firms. Finally, Hu et al. (2002) examine hazardous-waste reverse logistics systems. Although there is a vast literature on reverse logistics, most quantitative models focus on network design (i.e. location of joint facilities, allocation of returning materials to open facilities. etc.) and inventory control. To this end, few consider vehicle routing and scheduling with respect to the reverse collection or distribution activities. Among others, Dethloff (2001) addresses a reverse distribution and collection problem where re-usable packaging and recyclable goods had to be transported in the reverse direction for remanufacturing. Alshamrani et al. (2007) deal with a reverse blood distribution problem of the American Red Cross. Finally, Teixeira et al. (2004) present a case study for the recycling of solid waste in urban areas.

In order to determine the planning requirements of WLO collection and recycling various aspects must be considered. Although, the locations and capacity of the accumulation points network along with the available resources of both forward and reverse channels are prespecified, there is an interaction among them affecting both short and long term planning. More precisely, the customers' demand for lubricant products partly determine the Master Production Schedule (MPS), and consequently, the Material Requirements Planning (MRP). To this end, the MRP along with the sales forecasts and the inventory policy determines the WLO daily collection requirements. Although inventory plays the buffer role between production and collection, practically, one has to devise a production schedule that allows for a compromise between production effectiveness, inventory handling costs and collection vehicle resources. On the other hand, production planning partly determines distribution schedules of lubricant products to final customers.

From the operational viewpoint, on a daily basis, given the desired production plans and the current inventory status, the scheduler has to determine the collection requirements and define which collection and accumulation points will be serviced. Subsequently, the scheduler has to determine the associated collection routing plans. In particular, sets of collection vehicle fleets located at accumulation points, collect (pickup) WLO from collection and accumulation points and transport them either to the respective accumulation points or to the central storage facility of the regeneration plant. Similarly, the scheduler has to determine the daily distribution plans of lubricant products to customers. To-date, planning is empirically performed, without considering the MPS, inventory, availability of resources and other important factors. Thus, a web-based DSS is developed to address planning and monitoring needs of both collection and distribution operations. The latter need is further reinforced by the explosive number of the collection points participating in the recycling operations and the strict laws imposing the collection of used lubricants.

The rapidly growing interest on developing DSS and the appropriate OR methodologies and tools that could aid logistics managers to lower costs and achieve greater flexibility, has attracted significant attention from researchers (Tarantilis et al., 2005). The advances in ICT and the emergence of accurate spatial information systems have provided all technical prerequisites that enable companies to integrate vehicle fleet routing and scheduling with other key functions. In the context of modern telecommunication systems, Electronic Data Interchange (EDI), Global Positioning Systems (GPS) and Geographic Information Systems (GIS) are the main enablers of fleet management within enterprise wide end-to-end information systems.

Generation of vehicle routing plans require access to spatial sub-systems, network optimization procedures and particular geo-processing spatial tools provided by GISs using specialized spatial data storage formats. The combination of DSS and GIS functions provides the framework for vehicle routing DSS as they synthesize decision making tools and routing algorithms with spatial tools including the ability to provide visual feedback in the form of maps. Such systems are also referred as Spatial decision support systems (SDSS)(Sharma et al., 2006). A wide variety of vehicle routing DSS appears in literature, including distribution systems (Tarantilis and Kiranoudis, 2001; Tarantilis and Kiranoudis, 2002a; Tarantilis and Kiranoudis, 2002b), collection (Butler et al., 2005), dispatch and delivery (Weigel and Cao, 1999) and ship scheduling (Fagerholt, 2004; Sambrakos et al., 2004). Other more recent examples of vehicle routing DSS can be found in Belenguer et al. (2005), Tarantilis et al. (2004b), Ioannou et al. (2005) and Ruiz et al. (2004).

Most of the aforementioned DSSs fall into the category of model-driven single-user systems, where core routing problems are modeled and solved using optimization methods supported by peripheral spatial tools (Ray, 2005). To the other end, given the increasing need to better support group decision making, research moves towards to larger multi-user enterprise wide systems which facilitate centralized–regionalized vehicle routing DSSs. As stated by Hall (2006), centralization is allowing companies to aggregate data and monitor the overall performance. Obviously, such capabilities and integration with other peripheral functional modules are mainly being provided through web-based systems that enable sharing of information and algorithms among multiple sites. Additional advantages of web-based DSS include platform independence, shorter learning curves for users already familiar with web tools, lower software distribution costs and ease of performing system updates (Tarantilis et al., in press).

The movement towards web-based DSSs allows planning or optimization tools to be distributed more widely, since all decision support related operations are performed on network servers. Recently, Prindezis and Kiranoudis (2005) developed an internet based logistics management system to co-ordinate and disseminate tasks and related information for a real life meat distribution system. Ray (2005) developed a web-based DSS for managing the movement of oversize-overweight vehicles over highways. Finally, Tarantilis (2006) proposes a vehicle routing DSS developed in a way that allows it to be used as a web-based Application Service Provider (ASP). Similar to internet service providers, that linked businesses and consumers up to the internet, ASPs lease software applications to businesses and consumers via the internet.

In this paper, the systemic dimension and the modular architecture of the proposed web-based DSS is illustrated. Emphasis is given on the integration of online monitoring and reporting with other planning tools such as MRP, inventory control, shortest path, vehicle routing and their respective interactions and interrelationships. Particularly, the way to setup efficient collection and distribution channels is analyzed, along with the decisions that have to be made with respect to the actors participating (collection & accumulation points) and the possible interaction between production and collection processes. Additionally, for both WLO collection and lubricant distribution problems, sophisticated hybrid metaheuristic methodologies are proposed and incorporated to the DSS. Finally, the system design and implementation experience to an actual industrial environment is reported, while configuration, testing and system benefits are also discussed.

The remainder of the paper is organized as follows: Section 2 presents all aspects and operational realities of WLO collection, recycling and lubricant distribution operations. Section 3, illustrates the proposed web-based DSS system structure followed by a detailed presentation of all functional modules. The emphasis is on the systemic dimensions, while a thorough analysis of the mechanisms and attributes of the integrated OR methodologies and tools is provided. Section 4, discusses the characteristics of the case study company, the project phases and the progress of implementation along with the immediate and future benefits. Finally, the paper concludes in Section 5, offering also pointers for further research.

2. Problem description – operational realities

2.1. Upstream movement of WLO – collection stages

Waste lube oils can be found at several places, such as gas stations, automobile workshops, production sites, industrial facilities and others, all referred as *collection points*. The WLO collection and regeneration processes involve the upstream movement of WLO from several sets of collection points to intermediate transfer *accumulation points* and to the central regeneration and storage facility (central accumulation point), where new lubricants are produced. Fig. 1 illustrates the movement of WLO from collection and accumulation points to the central storage facility. The WLO collection operations involve three distinct and interrelated stages, i.e., from several sets of collection points to the corresponding accumulation points (2nd stage), and directly from collection points (1st stage) or accumulation points (3rd stage) to the central accumulation point of the regeneration plant. Subsequently, WLO is regenerated and basic lube oils are produced, which are further mixed in appropriate analogies with chemicals and additives to form a series of lubricant products.

The majority of collection points and the central regeneration and storage facilities are located at the metropolitan area of Athens, Greece. On a daily basis, a set of heterogeneous vehicles, called *collection vehicles*, collect (pick-up) different grades of WLO from a set of collection points and transport (deliver) them to the central accumulation point, where WLO is stored. The case where collection vehicles pick-up WLO from collection points and deliver it to the central accumulation point, will be referred as 1st *collection stage*.

On the other hand, there is a considerable amount of collection points, especially industrial facilities and production sites, that are spread all over Greece. These collection points are serviced through a network of WLO intermediate storage/accumulation facilities, called *transfer* or *accumulation points*. These are mainly used to accumulate and store locally the collected WLO. Furthermore each accumulation point has a preassigned area of responsibility, and therefore, each collection point is assigned to a specific accumulation point. It is assumed that the coverage of the overall network is satisfactory and all collection points can be serviced within a daily planning horizon. Similar to the 1st collection stage, on a daily basis collection vehicles originate at accumulation points (local vehicle depots), pick-up WLO from the corresponding collection points and deliver it to the respective accumulation point. The latter case will be referred to as 2nd *collection stage.*

The final collection stage considers transportation of WLO from local accumulation points to the central accumulation point and will be referred as the 3rd collection stage. Both the 1st and the 2nd stages of collection are

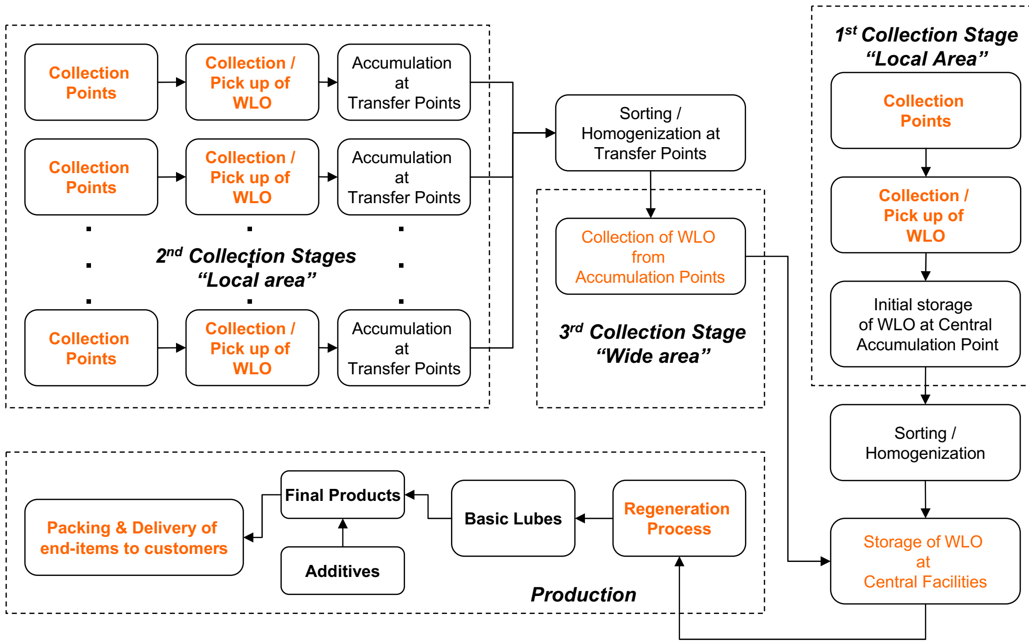


Fig. 1. The upstream movement of waste lube oils – collection & regeneration.

mostly performed in *local* (urban) areas using intra-city road networks with vehicles of small size. On the contrary, vehicles associated with the third collection stage (pick-up of WLO from accumulation points) are of larger size in order to carry large quantities and perform *wide* area routes mostly through the primary and secondary highway network infrastructure. For this reason vehicles assigned to the 3rd collection stage will be referred as *transfer vehicles*.

2.2. Re-usability of WLO

A particular feature of WLO collection and regeneration, is the quality level of the returns or similarly the re-usability of the collected WLO. The factor that determines the WLO quality level (grade) is the percentage concentration of other admixtures contained, such as water, carbon, sea water and so on. From the regeneration viewpoint, the regeneration plant can treat only WLOs with particular quality specifications. Thus, prior regeneration WLOs are subject to a homogenization pre-process. The latter takes place either at the central regeneration facility or at the local accumulation points, and depends directly on the quality of the collected WLO.

Typically, the homogenization pre-process involves the blending of low quality WLOs with other of higher quality or blending with basic lube oils (actual output of regeneration). Obviously, the respective homogenized quantity of low quality WLOs decreases, and furthermore, the overall regeneration processing times are larger. Thus, the efficiency of regeneration (amount of regenerated basic lube oils produced versus regeneration processing times) is analogous to the quality of the collected WLO. Practically, each quality grade constitutes a different WLO commodity. For this reason, during collection these commodities are stored separately into different vehicle compartments.

2.3. Nature of collection points

The collection points are distinguished into *minor* and *major*. At minor collection points (e.g. petrol stations, automobile repair shops and other) the available quantity of WLO and the respective accumulation rates are relatively small. On the other hand, major collection points (e.g. production sites and industrial facilities) produce large quantities of single graded WLO, with near constant accumulation rate. Obviously, during collection planning, the size of pickup quantities plays an important role; therefore, one may expect the nature of collection points serviced to affect the collection schedules.

2.4. Interaction between collection and regeneration

All WLO collection operations follow a restricted cycle that is repeated daily (5 days per week) and involve several operational realities. The major source of practical complexities is that WLO comes in multiple quality levels, while variations may occur between planned and actual collected quantities. This is due to the fact that in many cases only estimates, based on historical data, can be made for the availability of WLO at collection points. Obviously, supply mistrust in terms of returned quantity can limit production in case there is insufficient feed from collection points, while mistrust in the returned quality may cause production inconveniences and lower throughput.

Contrary to WLO collection operations, the regeneration process is performed in a non-stop 24×7 basis. As mentioned, there is an evident interaction between production and collection. More precisely, the actual regeneration requirements, and thereafter, the WLO collection needs, are determined by the customers' aggregate demand for new lubricant products. These collection requirements can be obtained using an MRP procedure given the actual MPS, the production forecasts and the confirmed sales orders. However, there are two aspects that must be considered in order to determine material requirements and plan production accordingly. The first is supply mistrust and the second is the limited WLO quantity that can be collected using the available fleet of vehicles for a given planning horizon. Therefore, an effective inventory management policy must be developed that captures all these critical aspects.

Inventory can be viewed as the absorber of WLO daily collection level variability and customer demand. Therefore, the production plans do not affect local WLO collection but only the inventory movements. Although, the holding of excessive inventory smooths collection level variability, the inventory holding costs increases. On the other hand, there is a minimum inventory required to ensure the non-stop operation of the production due to shortages. Therefore, production planning and inventory management affect significantly vehicle routing and collection requirements (size of pickup quantities). Obviously, for a given time horizon, the larger the ratio between the amount of collection points that need to be serviced and the respective size of pickup quantities, the larger is the number of collection points serviced per route.

The overall operational framework can be viewed as follows. First, the MPS is obtained exclusively by customers' demand forecasts and sales orders already confirmed. Subsequently, based on end-item lubricants MPS demands, the traditional MRP routines generate the WLO gross requirements for a given period. Note, that both MPS and MRP functionalities are offered by standard ERP system modules. Consequently, the net regeneration requirements can be calculated based on WLO inventory status and policy. In terms of inventory management, a typical inventory model is proposed in order to determine the planned regeneration requirements. Finally, the scheduler has to determine the actual requirements of each collection stage along with the sets of collection points that will contribute to the desired collection quantity. At this point, the main effort is to propose the appropriate decision making tools in order to manage historical data and to model collection points' service urgency.

2.5. Collection of WLO

Having defined the planned collection requirements for each collection stage and accumulation point, and the respective collection points that will be visited, the vehicle routing plans can be determined. The WLO collection problem can be accurately described as follows. On a daily basis, a heterogeneous fixed fleet of depot-returning collection vehicles with multiple storage compartments, collect (pickup) different commodities of WLO from a set of collection points, and transport it to the respective accumulation point (depot). Collection points are geographically dispersed within a distance radius that allows for collection to be performed on a daily planning horizon. Furthermore, each collection point's WLO availability along with its respective quality are known when the collection schedule is determined, as is the distance and travel time between the accumulation point and each collection point, as well as between all pairs of collection points. Finally, each collection point is serviced only once by exactly one vehicle, without violating capacity and loading restrictions. The total collection cost of a vehicle is the sum of the associated fixed and variable cost incurred proportional to the traveled distance. The objective is to determine minimum cost fleet size and mix, following routes of minimum distance, within the restrictions imposed by the available fleet composition.

An important source of complexity is the multiple commodity nature of WLO, which also imposes particular loading constraints. These commodities must be kept into separate vehicle compartments during one vehicle route of a daily collection schedule. For this reason, every vehicle is equipped with multiple waterproof compartments able to accommodate all commodities, each characterized by a distinct capacity. In the literature, routing problems where vehicles are equipped with two or more compartments are known as Multiple Compartment Commodity Vehicle Routing Problems (MCCVRP). Recently, Ruiz et al. (2004) develop a DSS for a real life MCCVRP considering that each vehicle's compartment is coupled (assigned) with a specific customer order. Thus, the number of customers serviced is proportional to the number of available compartments. On the other hand, the WLO collection problem is more generalized, since compartments are coupled only with the commodity carried during a vehicle route. To this end, the loading of vehicles is further complicated since the available vehicle fleet is heterogeneous both with respect to the capacity and to the number/volume of compartments equipped with.

The associated WLO vehicle loading problem can be described as follows: determine the loading (packing) of several WLO commodities of different volume into a finite number of compartments (bins) of different capacity without violating capacity constraints such that the minimum number of compartments is used or the total free available capacity of a vehicle is maximized. Note that according to our survey the MCCVRP with the above loading restrictions and heterogeneous fleet of vehicles has not been addressed in literature before.

2.6. Distribution of lubricant products

The daily delivery of lubricant products to customers is a typical distribution system which can be described as follows. Consider a depot where several products, have to be delivered in relatively short times to a set of customers. The latter are geographically dispersed within a distance radius that allows for demand to be satisfied through daily deliveries. Furthermore, assume that each customer's demand is known when the delivery schedule is determined, as is the distance and travel time between depot and each customer, as well as between each pair of customers' locations. Additionally, the time interval during which the delivery has to take place is also known. This interval is bounded by the earliest and latest time during the day that the delivery to a particular customer has to be completed. The goal is to determine the minimum number of vehicles that are required to service all customers following the paths of minimum distance.

An additional feature that must be taken into account is that all distribution functions are allocated to a third party logistic (3PL) provider. In our case, the 3PL provider invoices according to the total distance traveled from the depot to the final customer that each vehicle services. Therefore, after all deliveries have been performed, vehicles do not return to the depot, and the delivery process is terminated as soon as the final customer is served. When all deliveries are completed, the travel distance and time associated with each vehicle is logged and drivers are free to return to their preferred location, since this portion of travel is not reimbursed. Such problems are known as Open Vehicle Routing Problems (OVRP) (Sariklis and Powel, 2000).

3. Decision support system

WLO collection and regeneration are complex processes, and the proposed DSS has to address all issues pertaining the production, inventory, collection and distribution functions. The four major questions that the DSS must tackle are: (i) how much WLO must be available at the central accumulation point in order to allow for smooth production; (ii) how to effectively schedule the collection process performed by heterogeneous vehicle fleets, considering all operational constraints; (iii) how to continuously monitor collection operations and accumulation rates to ensure full WLO retrieval (since WLO can also be used as cheap oil substitute), and (iv) to provide the appropriate decision making tools for the effective and efficient distribution of lubricant products to customers. The proposed DSS conceptual architecture is described below.

3.1. DSS system structure

The architecture of the proposed DSS involves an integrated framework of GIS technology coupled with interactive communication capabilities among peripheral tools. For the operational framework described above, the DSS conceptual structure, consists of the following modules: the Reverse MRP, the Planning System, the Fleet Management System (FMS) and the Waste Monitoring Application. Fig. 2 shows the interrelationships among them as well as the environment, including the Database and the ERP system.

The central component of the DSS structure is FMS, which is the main web-browser user interface. The basic functionality of FMS includes navigation screens to all functional modules, database input, output and update as well as capability of producing visual outputs and several kinds of reports. The proposed DSS utilizes a built-in relational database which contains several sets of tables that handles spatial, historical, static and real time on-line data able to fulfill the needs and relationships of each functional module. All data entry fields can be changeable or permanent.

Effective data management plays an essential role in the smooth functionality of the system. This becomes more crucial when the collection takes place within large city road networks. For example, the validation and verification of addresses and co-ordinates (i.e. latitude and longitude) of collection points and customers ensure to the extent possible the accurate estimation of traveling times and distances. In the case of bounds in the total duration,

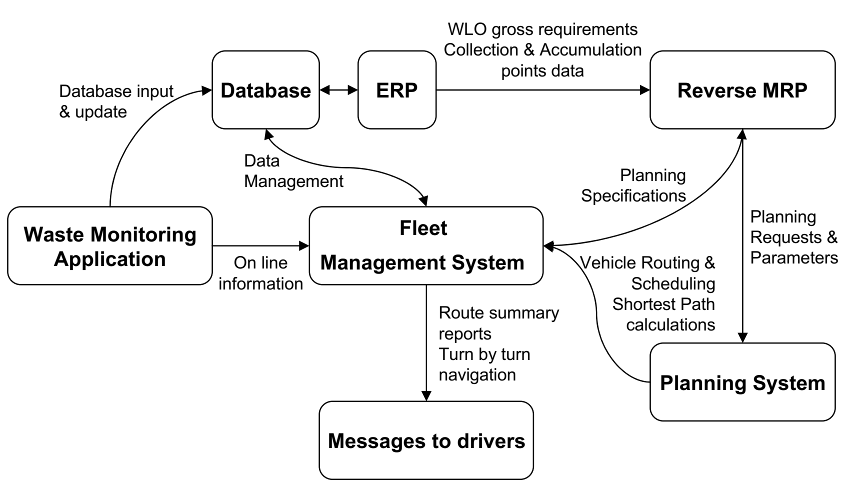


Fig. 2. DSS system structure.

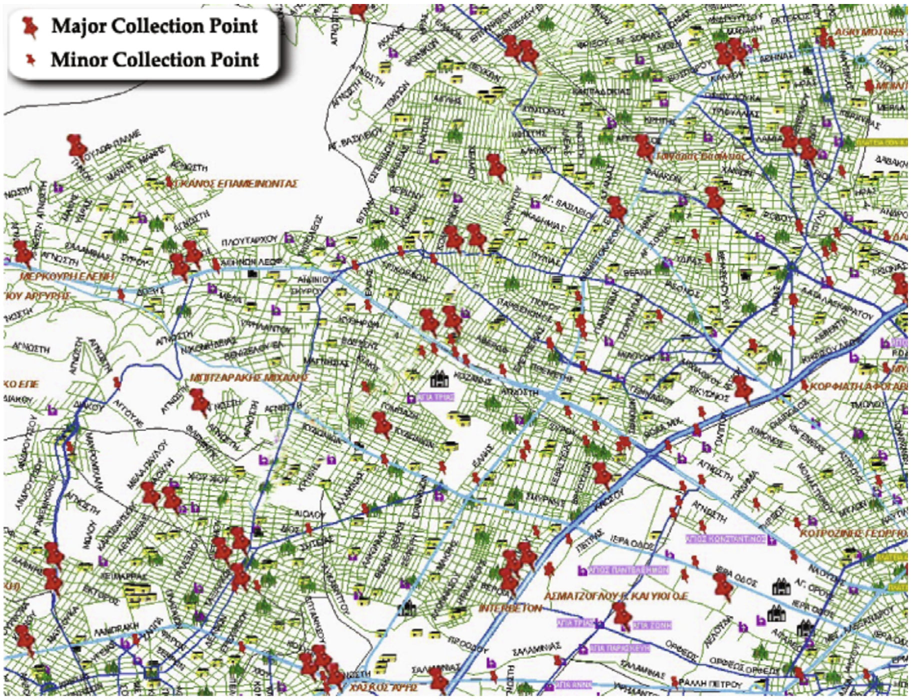


Fig. 3. Sample view of major and minor collection points locations.

underestimation of travel time may lead to failure of the routing plan, whereas overestimation may lower the utilization of vehicles, and cause unproductive waiting times (Prindezis and Kiranoudis, 2005). For this reason, enhanced geocoding tools have been developed that enable matching of addresses and road segments with the respective locations on digital maps. Fig. 3 presents a sample view of major and minor collection points' locations, highlighted with large and small marks, respectively.

As mentioned earlier, several control variables are updated either in real time by Waste Monitoring Application or on a daily basis through replication from the ERP system database. In the first case, the scheduler through FMS can monitor the overall performance of collection operations and the WLO accumulation rates at accumulation points and selected major collection points. The latter is enabled by following the update status of control objects, i.e., vehicles, position, vehicle compartment levels, inventory levels, collected quantities, paths followed (traveling times, etc.) and others, displaying the results in both graphical and tabular forms. Additionally, the scheduler is able to monitor the current schedule status, that is, the exact location and the current collection activities, in order to act immediately in cases of environmental danger or other adverse situations. To the other end, information provided from ERP is important to aid the scheduler to set up planning requests and determine all associated parameters using the Reverse MRP and the Planning System's modules. Finally, ERP provides all confirmed sales orders for the next planning day in order to aid the scheduler to determine the daily distribution plans.

The Reverse MRP module provides the set of collection points to be serviced and estimates the quantity of WLO required for regeneration. Initially, the scheduler is requested to determine the daily collection requirements and decide which stages of collection will contribute to the desired quantity and to what extent. The next step is to determine the sets of collection or accumulation points to be visited for each stage of collection. Finally, the Planning System module is triggered. The latter employs sophisticated optimization methods for computing shortest paths and for solving the associated vehicle routing and scheduling problems. On request, it calculates the corresponding paths, estimates travel times and distances and provides the complete schedule of all planned collection operations. That is entailing an assignment of stops to routes and terminals, sequencing stops and routing vehicles between pairs of stops. These results are displayed through FMS in such a way that the scheduler can guide the solution process and communicate results providing turn by turn navigation and route summary reports to the collection vehicles.

Finally, similar is the framework for the scheduler to determine the daily distribution plans of end-item lubricant products to final customers. Given from the ERP system all confirmed sales orders for the next planning day, the scheduler approves or modifies the list of customers needed to be serviced. Next, the scheduler selects the available hired vehicles and the Planning System is triggered. On request, the complete schedule is determined, while the results are displayed both in graphical and tabular form, providing turn by turn navigation and route summary reports to the distribution vehicles. Upon termination of the distribution process, the start times of service are logged and comparison between actual and planned distribution schedules is made.

3.2. Reverse MRP

The Reverse MRP component models the service urgency of collection points, estimates the quantity of the WLO required for regeneration and determines the actual planning requests. Initially, given the output of the MRP (WLO gross requirements), an inventory model is used to estimate the WLO volume that must be collected on a daily basis in order to ensure that production is met and no stock-outs occur. Furthermore, several filtering procedures are employed to assign priorities (service urgency) to collection points. More specifically, priority lists of collection points are created for each accumulation point, while the scheduler is prompted to approve or modify the lists. Based on the priority lists, the WLO collection needs and the available resources, the scheduler must determine the collection requirements and the sets of collection points to be visited (service lists) for each collection stage.

The primary role of the Reverse MRP module is to “link” the actual regeneration requirements with the collection planning needs. As illustrated in Fig. 4 using ERP/MRP, the WLO requirements are generated and filtered by the Regeneration Requirements component that also considers current inventory status. Having calculated net regeneration requirements Q, using a random yield inventory model the planned regeneration requirements are determined. Since, the replenishment quantity (the quantity finally collected) is a stochastic variable which might induce irregularities to the production process, the desired quantity Q is changed to $\dot{Q}$ by the model, for a given confidence level.

Having determined the quantity to be available at the central accumulation point and estimated the WLO quantity that must be ordered, the contributions of both 1st and 3rd collection stages must be defined. The Regeneration Requirements component splits the WLO collection requirements with respect to the available vehicle resources, considering both collection stages with lead times of one and two days, respectively. To the other end, the daily collection activities of all accumulation points participating in the 2nd collection stage is performed based on the available vehicle fleet storage capacity. Subsequently, the scheduler must prioritize collection points based on their service urgency and determine the corresponding set (service list) of collection points to be visited using the Collection Points Prioritization component. The latter features a specialized heuristic which assigns priorities to the collection points that model their service urgency using both on-line and historical data.

Finally, having determined the planning requests and their associate parameters, the Planning System module is triggered (see Figs. 4 and 7). The latter returns high quality routing plans and the respective shortest paths. It is worth mentioning, that although the sorted lists are generated by the system, the scheduler is prompted to approve or modify the lists and all associated parameters and specifications according to other operational realities. Thus, continuous dynamic interventions can be made on the existing planning requests in order to satisfy changes in existing routing plans. The Reverse MRP module then redesigns these new planning requests and feeds accordingly the Planning System module.

3.2.1. Random yield model

Bassok et al. (2002) state that uncertainty in a production system is mainly of three types: (a) demand, (b) production and (c) supply uncertainty. Demand uncertainty occurs due to unknown customer behavior and lack of robust forecasting models, while production uncertainty occurs due to stochastic processing times and random breakdowns. The former can be handled by efficient MPS, customer negotiations, overtime and spare capacity. However the most difficult form of uncertainty, in terms of efficient and effective handling, is the supply uncertainty of raw materials also referred to as the random yield problem.

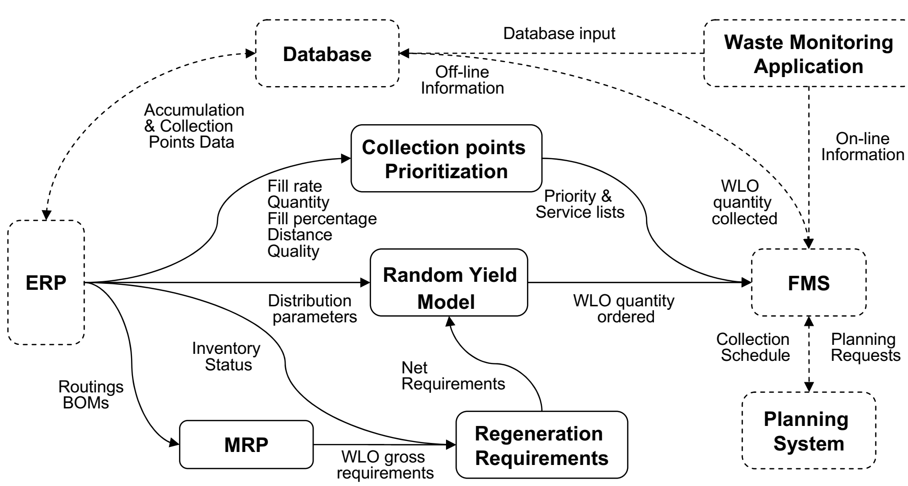


Fig. 4. Reverse MRP module and its environment.

In the literature several models and approaches have been proposed.

Among others, Shih (1980) developed a model assuming that the ratio of items delivered to items ordered is always less than one. Ehrhardt and Taube (1987) dealt with a single period model assuming no interaction between two adjacent periods. Parlar and Perry (1995) considered the case where the raw material is either available or not in a given period (either $Q = \dot{Q}$ or $\dot{Q} = 0$). Bassok et al. (2002), developed a random yield model without considering the case of yield factor values more than one (the case that the collection quantity can be greater than the quantity ordered). More recently, Fleischmann et al. (2005) dealt with a reverse logistics problem and modeled the random yield of used components, using a Poisson distribution to determine the demand pattern. In our case, the period is one day and the collection quantity in period p heavily depends on the collection quantity in period $p-1$. Therefore, the multi-period case must be examined, assuming that for all periods demand is known (output of MRP).

The MRP system outputs the overall WLO quantity required to produce the desired quantities of new products, which are the input to the Regeneration Requirements component. Let p denote the period that the Regeneration Requirements is executed and G_p be the gross requirement for WLO in that period. In particular, the gross requirements G_p and G_{p+1} are considered (also output of the MRP module), as well as the current inventory level Il_p (inventory status), to determine the net requirements of WLO Q_p for the corresponding period p. Records of inventory status, safety stock level ss and target inventory level M are maintained with the ERP system. A typical inventory movement for a number of periods is presented in Fig. 5.

Due to supply mistrust, it is expected that the WLO inventory level after the daily collection (Il_{p+1}) will be different than M (ideally it is equal to M). As shown in Fig. 5, inventory variations are linear because the production rate of the regeneration process is constant throughout a working day. Another fact is that the regeneration procedure occurs in an almost constant rate and the WLO supply cannot be throttled to decrease the regeneration rate in case of WLO stock-out. If this happens, the regeneration plant must be shut down and its restarting is associated with very high setup costs.

The random yield component uses the collection efficiency ratio α and determines the total WLO quantity $\dot{Q}_p$ required for collection at period p. Recall that collection efficiency is defined as the ratio between collected and ordered WLO. A possible shortcoming is that collection efficiency is considered irrelevant to the ordered quantity. However, the variability of collection efficiency for various days is very small and thus, the above rationale can be used to estimate the planned collection quantity. Based on historical data, variable α follows a normal distribution with parameters μ_α (mean) and σ_α (standard deviation) and the quantity to be ordered $\dot{Q}_p$ can be estimated. More specifically, the quantity $\dot{Q}_p$ is the WLO quantity that if ordered, will result in the WLO collection of at least Q_p quantity, for a given confidence level cl.

Another important parameter of inventory control is the safety stock level ss, required to ensure a smooth operation of the regeneration plant. The parameters needed to calculate the safety stock level are: (a) the mean daily WLO demand $\overline{Q}$, (b) the standard deviation of WLO daily demand $\sigma_{\overline{Q}}$, (c) the days of normal operation if no WLO is collected J_{ss} and (d) the degree of certainty or confidence level cl. The safety stock ss can be easily calculated as follows:

$$ss = J_{ss}\overline{Q} + zJ_{ss}\sigma_{\overline{Q}}, \tag{1}$$

In (1) z depends on the degree of certainty cl required (degree of certainty that no stock outs will occur within the J_{ss} time period).

3.2.2. Collection points prioritization

The Collection Points Prioritization module incorporates a heuristic that generates a sorted list of collection

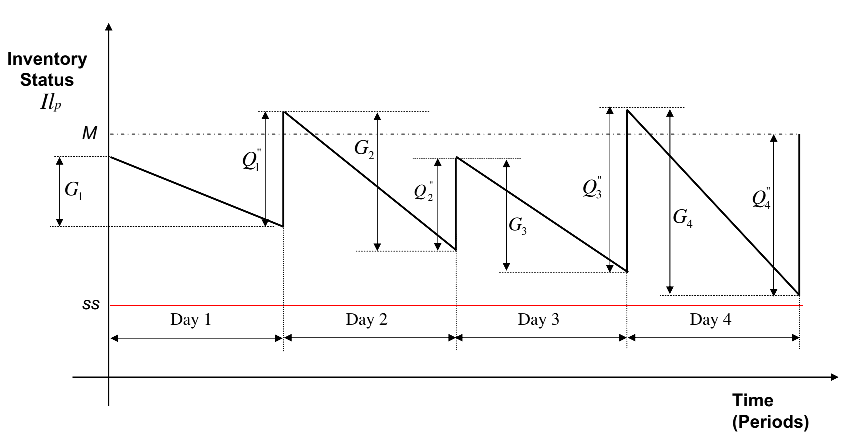


Fig. 5. Variations of WLO inventory level at the central storage facility.

points to be serviced for each respective accumulation point g. Let i denote the index of collection points; the proposed heuristic takes into account the following controlled variables in order to generate priority and service lists:

- Average fill rate F_i, with respect to the quantity accumulated per time unit.
- Available quantity Q_i^q, known or estimated that can be collected from i of quality grade q.
- Fill percentage L_i, ratio between the available quantity Q_i^q and the total storage capacity availability.
- Distance from corresponding accumulation point D_{ig}.
- Quality level q_i of collection point i.

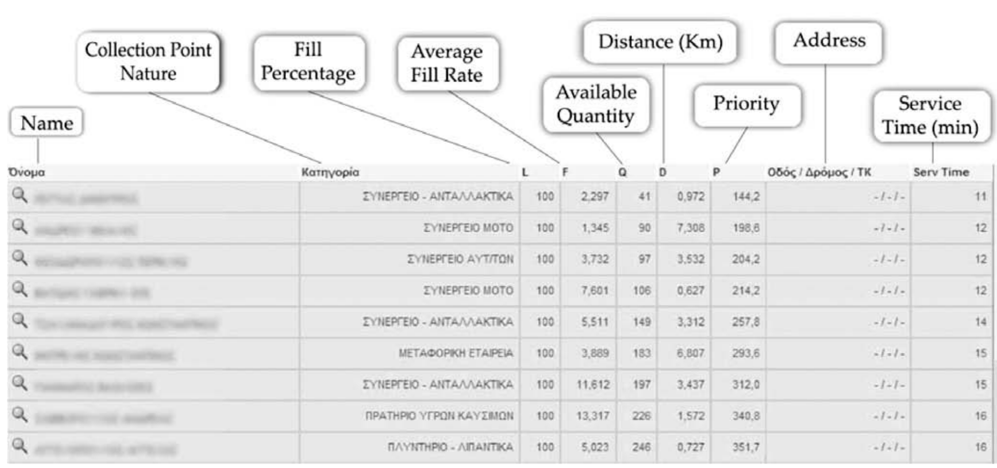
All aforementioned control variables are known in case of major collection points with online monitoring; for the remaining ones, historical data is used to estimate them. For this purpose appropriate forecasting functions offered by the ERP system are utilized. Let $P_{i,g}$ denote the priority of collection point i that belongs to accumulation point g, W_1 the weight of the fill percentage, W_2 the weight of the fill rate, W_3 the weight of the WLO availability and W_4 the weight of the distance from the corresponding accumulation point. The cost function for each collection point i is calculated with respect to the weighted linear combination of all components as follows:

$$P_{i,g} = W_1 L_i + W_2 F_i + W_3 Q_i + W_4 D_{ig}, \tag{2}$$

Using the cost function (2), a sorted *priority list* pl_g is generated for all accumulation points g. These priority lists must be cropped accordingly to form the so called *service lists* sl_g (see also Fig. 6). The service lists must account at least the minimum WLO quantity expected to be collected and also consider the variation of WLO quality. As mentioned, the pre-processing homogenization phase performed at each accumulation point assumes a WLO of standard quality. For this reason, the collection points must be selected in such a way that the final homogenized collected WLO meets certain specifications.

Let Q'_g denote the quantity planned to be collected from accumulation point g, $\bar{q}$ the standard quality of homogenized WLO and Q''_g the maximum capacity that the allocated vehicle fleet to accumulation point g can hold. Obviously, for all accumulation points g each service list must satisfy the following conditions: $Q'_g \leqslant Q''_g$ and $\sum_{i \in sl_g} Q_i^q q_i \geqslant Q'_g \bar{q}$. The standard quality $\bar{q}$ and the quality level q_i of each collection point can be found in the corresponding specification table. This table contains all quality levels normalized with respect to the standardized homogenized WLO quality grade. Therefore, the overall quality level q_{sl_g} of service list sl_g, can be calculated as $q_{sl_g} = \frac{\sum_{i \in sl_g} Q_i^q q_i}{\sum_{i \in sl_g} Q_i}$. The proposed heuristic can be described as follows:

Service lists ($\dot{Q}_g$)
For all accumulation points g
  For all collection points i assigned to g
    Add collection point i to priority list pl_g
    Calculate $P_{i,g} = W_1 L_i + W_2 F_i + W_3 Q_i + W_4 D_{ig}$
  EndFor
  Arrange elements i of pl_g in descending order of $P_{i,g}$
  Initialize sl_g list ($sl_g \leftarrow 0$)
  Do
    Add the first collection point i of pl_g to sl_g
    Remove collection point i from pl_g
  While $\dot{Q}_g \leqslant \sum_{i \in sl_g} Q_i^q$
  Calculate q_{sl_g}
  While $q_{sl_g} \leqslant \bar{q}$ AND $\dot{Q}_g \geqslant \sum_{i \in sl_g} Q_i^q$ **Do**
    Add collection point the first j of pl_g to sl_g with $q_j > \bar{q}$
    Remove collection point j from pl_g
    Arrange collection points i of sl_g in descending order of q_i
    Remove the last collection point i from sl_g
    Calculate q_{sl_g}
  EndWhile
EndFor
Return all service lists sl_g



Όνομα	Κατηγορία	L	F	Q	D	P	Οδός / Δρόμος / ΤΚ	Serv Time
[illegible]	ΣΥΝΕΡΓΕΙΟ - ΑΝΤΑΛΛΑΚΤΙΚΑ	100	2,297	41	0,972	144,2	- / - / -	11
[illegible]	ΣΥΝΕΡΓΕΙΟ ΜΟΤΟ	100	1,345	90	7,308	198,6	- / - / -	12
[illegible]	ΣΥΝΕΡΓΕΙΟ ΑΥΤ/ΤΩΝ	100	3,732	97	3,532	204,2	- / - / -	12
[illegible]	ΣΥΝΕΡΓΕΙΟ ΜΟΤΟ	100	7,601	106	0,627	214,2	- / - / -	12
[illegible]	ΣΥΝΕΡΓΕΙΟ - ΑΝΤΑΛΛΑΚΤΙΚΑ	100	5,511	149	3,312	257,8	- / - / -	14
[illegible]	ΜΕΤΑΦΟΡΙΚΗ ΕΤΑΙΡΕΙΑ	100	3,889	183	6,807	293,6	- / - / -	15
[illegible]	ΣΥΝΕΡΓΕΙΟ - ΑΝΤΑΛΛΑΚΤΙΚΑ	100	11,612	197	3,437	312,0	- / - / -	15
[illegible]	ΠΡΑΤΗΡΙΟ ΥΓΡΩΝ ΚΑΥΣΙΜΩΝ	100	13,317	226	1,572	340,8	- / - / -	16
[illegible]	ΠΛΥΝΤΗΡΙΟ - ΛΙΠΑΝΤΙΚΑ	100	5,023	246	0,727	351,7	- / - / -	16

Fig. 6. Service list sample.

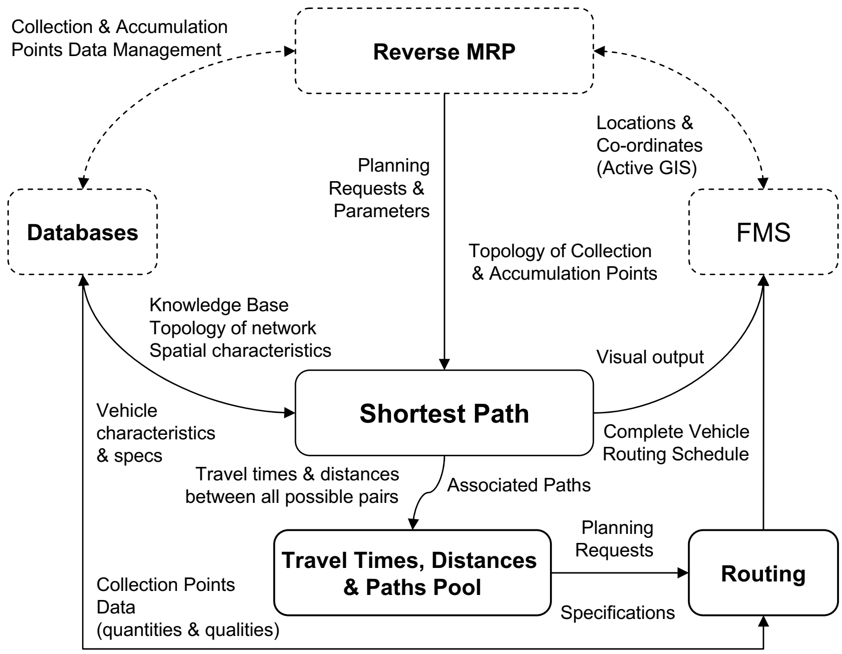


Fig. 7. Planning System module and its environment.

Such service lists are generated for each accumulation point. At this point, the scheduler contact each corresponding collection point appeared in the service list in order to verify the forecasted data (i.e. available quantity and fill percentage) and arrange the service for the next planning day. Subsequently, the new data provided by each collection point update the current forecasted data and if large deviations occur the scheduler is prompted to redesign the priority list. The above procedure ensures that the Planning System module works on actual data. Finally, it is worth mentioning that a degree of flexibility is assumed in terms of total storage capacity at minor collection points.

3.3. Planning System

The Planning System module is the main computational engine of the proposed DSS (see Fig. 7). Given the planning requirements and specifications determined either by the Reverse MRP module (WLO Collection) or directly from FMS (distribution of lubricants), the Planning System returns high quality routing – scheduling solutions and offers complete turn-by-turn path navigation for each vehicle. On request, it calculates the corresponding paths, estimates travel times and distances and provides the complete schedule of all planned collection or distribution operations.

Initially, the shortest path constructs a pool of origin and destination matrixes computed by the shortest paths (in terms of travel time) among all possible pairs of collection points and between collection and accumulation points or between all possible pairs of customers and the depot. The shortest path module uses spatial and non-spatial data, and particularly:

– the planning requests and specifications,
– the topology (location and co-ordinates) of all collection and accumulation points or customers within their respective road network,
– the spatial characteristics, the topology and the knowledge base of the road segments of each network,
– the speed of the vehicles based on the spatial characteristics of the road network and the region within which they move.

Subsequently, the routing algorithm, using the pool of origin destination matrixes, produces high quality routing solutions. The information provided to the routing algorithm in case of WLO collection is the following:

– the collection planning requests and specifications (service list, etc.),
– the composition-synthesis of the vehicle fleet available at each accumulation point,
– the available quantity, quality (commodity) and service time of each collection point need to be serviced,
– the type, the fixed and variable cost, the number of compartments and the available capacity per compartment for each collection vehicle,
– the travel times and distances between all possible pairs of collection points.

Similarly, the information provided in case of distribution of lubricants is the following:

– the distribution planning requests and specifications (planning horizon, customers, etc.),
– the number of hired vehicles available for distribution activities and their capacity,

– the customers' demand, time window and service time,
– the travel times and distances between all possible pairs of customers.

In return, the routing algorithms produce the complete vehicle routing schedules. Based on these schedules, the user through FMS can offer complete turn-by-turn path navigation (verbal) to each driver. In addition, FMS provides visual representation of each vehicle route and all related information, such as the total cost, total traveling time, vehicle capacity utilization, service level and so on. Fig. 8 illustrates a sample collection vehicle routing plan that has been finalized by the scheduler.

Figs. 9a and b illustrate a sample of 25 collection points all depot pairs shortest paths and the corresponding vehicle routing solution. Finally, it is important to note that the scheduler has the flexibility to modify (edit) an existing routing scenario by adding or subtracting collection points or collection vehicles. The generation of different planning scenarios can be performed either by adjusting specifications directly through the Planning System or by redesigning from scratch the overall planning requests and specifications back to the Reverse MRP module.

3.4. Path computations

The path computations are performed based on the travel time (or similarly distance traveled) within a pre-specified road network, and employ an enhanced Dijkstra algorithm (Dijkstra (1959)). The main differences of our implementation compared to the originally proposed method, is the use of arcs (links) instead of nodes. The latter is due to the fact that actual network information like turning restrictions, U-turns, speed limits, link type, number of lanes and actual road segment preferences (knowledge base) were taken under consideration (see also Jiang et al. (2002) for a similar approach). However, the task of delivering shortest paths that follow actual road networks, complying with traffic patterns that favor main city arteries, large streets and roads with light traffic, is very demanding (Ioannou et al., 2005).

For the calculations of the travel times both spatial and non-spatial network data are used. In particular, the determination of the travel time for a specific road segment is sensitive to traffic patterns and also varies according to the speed limit, the length, the type and the number of lanes. In our implementation, average speeds were assumed with respect to pre-specified network zones. Furthermore, using appropriate adjustment weights, a weighted combination of the characteristics of each road segment is assumed, in order to provide a better estimate for the associated travel times and subsequently to produce the corresponding shortest paths. Employing Dijkstra's algorithm, travel times estimates and distance matrixes are produced among all possible pairs of collections points or customers and accumulation points or depots respectively.

Due to the hazardous nature of WLO, a point of importance is the selection of paths that are not close to aggregate population points, in order to reduce the number of people placed at risk. The latter depends on the route segments that characterize the underlying road network. For this reason, an appropriate knowledge base is built to handle logical attributes. Such an approach requires a setup phase in which each road segment is coupled with specific

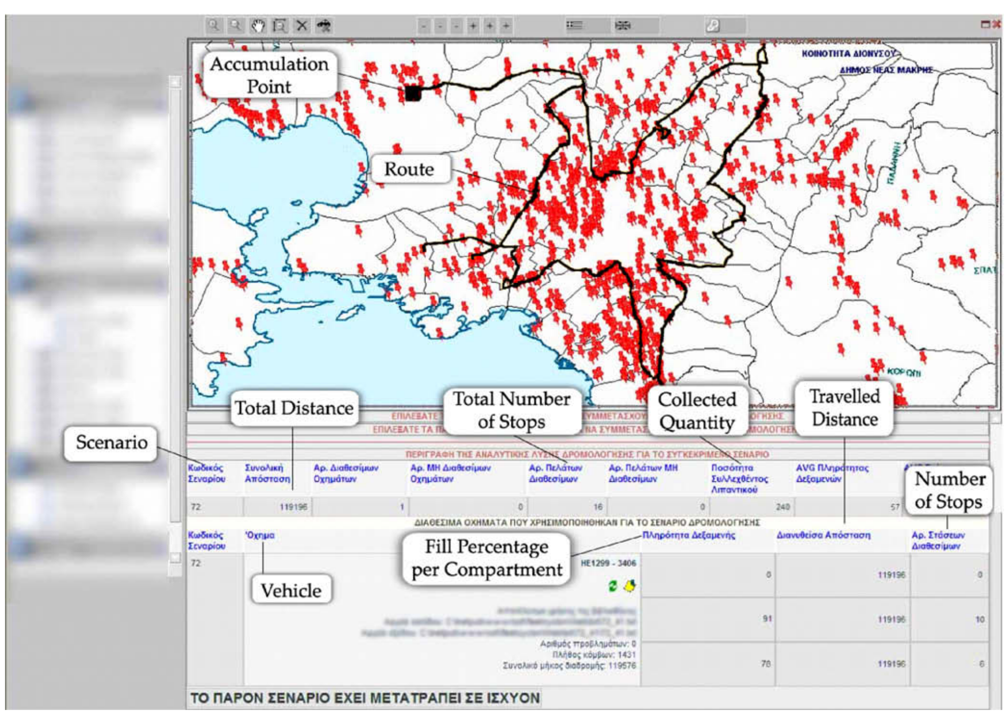


Fig. 8. Finalized collection vehicle routing plan.

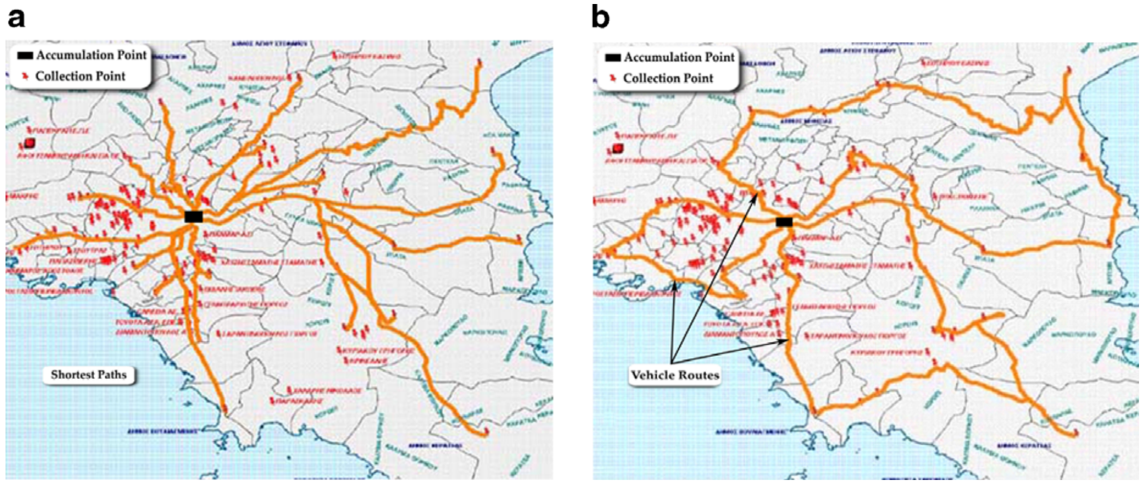


Fig. 9. All depot pairs shortest paths and the corresponding vehicle routing solution.

prioritization or preference attributes. The proposed knowledge base works as follows: Each road segment is characterized by a permanent preference label (low or high) based on the aggregate population of the greater area in which it belongs. From the implementation viewpoint, the overall network is divided into two sub-networks with respect to the priority which characterizes each link. Thus, segments with low priority are only considered when necessary to guarantee the connectivity of sub-networks.

Fig. 10 show a path computed by the proposed enhanced Dijkstra algorithm from an origin A to a destination node B with and without the use of the knowledge base, respectively. The path produced without the use of the knowledge base correspond to the shortest traveling time path (dashed line) from A to B. On the other hand, the path computed using the knowledge base is longer in terms of distance; however, it follows mostly segments labeled with high priority, compared to the shortest traveling time path, which mainly consist of low priority segments. Therefore, the paths produced by utilizing the proposed knowledge base can be denoted as lower risk paths.

3.5. Vehicle routing and scheduling

3.5.1. The WLO collection problem

Based on the problem description provided in Section 2.5, similar vehicle routing models, compared to the WLO collection problem, are the heterogeneous fixed fleet vehicle routing problem (HFFVRP) (Taillard, 1999; Tarantilis et al., 2004a,b; Tarantilis and Kiranoudis, 2007; Li et al., 2007) the HFFVRP with Time Windows (HFFVRPTW) (Paraskevopoulos et al., 2007) and the Multi-Compartment Commodity Vehicle Routing Problem (MCCVRP) (Ruiz et al., 2004). The HFFVRP considers a heterogeneous vehicle fleet composition with different capacities, fixed and variable costs, and particular availability (limited number of available vehicle types). The objective of HFFVRP is to determine the fleet size and mix of vehicles, originating

Fig. 10. Path computations using knowledge base on the road network of Athens.

and terminating at the depot, such that the sum of fixed and variable costs is minimized, or similarly to determine the optimal fleet composition with minimum routing costs.

On the other hand, the MCCVRP considers a fleet of vehicles that is equipped with two or more compartments and transport several commodities which must remain separate during transportation. The latter complicates matters since the loading of commodities with different volume into a finite number of compartments of different capacity, maximizing the total free available capacity of a vehicle, is not straightforward. Given the above specifications, the objective of the WLO Collection Problem is to determine the fleet of vehicles, originating and terminating at the corresponding accumulation point, such that fixed and variable costs are minimized, while each collection point is serviced only once by exactly one vehicle without violating vehicle capacity and loading restrictions.

The proposed solution methodology utilizes a List Based Threshold Accepting (LBTA) metaheuristic approach (Tarantilis et al., 2004a). LBTA is based on the principle of threshold accepting methods, and thus, it searches the solution space guided by a deterministic control parameter, called threshold. Therefore, non-improving solutions are accepted if the difference between objective functions of the current and the previously accepted solution are below a particular threshold. To this end, the proposed method utilizes a dynamically updated data structure-list to store the threshold values and to guide the search process. The proposed LBTA solution framework consists of the following steps as described below:

- *Step 1. Initialization:* The initial solution is produced by iteratively inserting an unassigned collection point in a partial constructed route, such that the utilization of the vehicles' capacity is maximized. Due to the multi-compartment multi-commodity nature of the problem, the feasibility of insertions with respect to the associated loading restrictions are also considered. For this purpose, a new heuristic algorithm has been developed as described subsequently.
- *Step 2. Local Search:* At the local search phase the effort is given on improving the solution quality in terms of distance traveled. Given a set of neighborhood structures a stochastic selection scheme is followed. A list of M elements is used to store the threshold values, while the list is dynamically updated during the search progress. The computation of the threshold values that represent the list of LBTA is described as follows:
- *Step 2(a).* Pick, at random, a neighboring solution s' of solution s, using a neighborhood structure.
- *Step 2(b).* Calculate the new threshold value $T_{\text{new}} = (f(s') - f(s))/f(s)$. If T_{new} is positive and lower than the maximum element of the list, $T_{\max}$, T_{new} is inserted into the list.
- *Step 2(c).* Repeat steps a and b until the list is filled up with M elements.
- *Step 3. List update*. New acceptances based on the maximum threshold value stored in the list at every iteration.
- *Step 3(a).* Pick, at random, a neighboring solution s' of solution s and calculate T_{new}.
- *Step 3(b).* If T_{new} is less than or equal to $T_{\max}$ of the list, s' is accepted and s is replaced by s'. The new threshold value T_{new} is inserted into the list, while $T_{\max}$ is removed. If $f(s) \leqslant f(elite)$ the best solution found *elite* is updated. To the other end, if $T_{\text{new}} > T_{\max}$, s' is not accepted, the list is not updated and a new local search phase is initialized.
- *Step 3(c).* Repeat steps a and b until no solution s' can be found to satisfy $T_{\text{new}} \leqslant T_{\max}$, for a number of iterations (stopping criterion).

The proposed loading heuristic algorithm can be described as follows. Let r_k denote a route performed by a vehicle k of a partial solution Ω, serving a set of collection points Ξ. Let H_q denote the aggregate quantity of a particular commodity q of all collection points $i \in \Xi$ such that $H_q = \sum_{i\in\Xi} Q_i^q$. Note that AC_r^k, FC_r^k and RC_r^k refer to the overall free available capacity, the total capacity available from unutilized compartments and the residual available capacity left at utilized compartments, respectively. The proposed loading heuristic, in a semi-parallel construction fashion, assigns quantities and couples compartments with particular commodities based on two criteria for commodity and compartment selection. The objective at each iteration is to load first the commodity q that maximizes FC_r^k, while the associate compartments assigned are those that minimize RC_r^k.

Initially, all compartments m of vehicle k are considered empty and H_q is calculated for all q. Next, each unloaded H_q is sequentially loaded temporarily into compartments and the associated FC_r^k is determined in the following manner: First the empty unutilized m' with maximum available capacity is identified. If m' can accommodate only part of H_q ($H_q \geqslant C_{m'}^k$), m' is marked temporarily as utilized, the residual left is set to 0 and H_q is reduced by $C_{m'}^k$ units. Otherwise, if m' can hold all H_q ($H_q < C_{m'}^k$), m'' that minimizes RC_r^k is selected, it is marked temporarily as utilized and H_q is set to 0. This procedure is repeated until H_q equals 0. Consequently, the FC_r^k obtained is stored, all temporarily marked compartments are re-initialized and the overall procedure is repeated for all unloaded commodities H_q. Next, the $H_{\hat{q}}$ of $\hat{q}$ that maximizes FC_r^k is loaded and the associated compartments are permanently marked as utilized. The latter procedure iterates until all commodities are loaded or terminates if the vehicle cannot accommodate the demands of all collection points $i \in \Xi$.

3.5.2. The lubricant distribution problem

Given the operational framework provided in Section 2.6 the Lubricant Distribution Problem can be formulated as an Open Vehicle Routing Problem with Time Windows (OVRPTW) (Repoussis et al., 2006). The OVRPTW seeks to design a set of minimum cost routes, each originating from the depot, using a fleet of vehicles with homogeneous characteristics, to service a set of customers with known demands within predefined time intervals (time windows). Each customer must be serviced only once by exactly one vehicle, while the total demand of a route must not exceed the capacity of the vehicle assigned. The distribution cost of a vehicle is proportional to the distance traveled as soon as the final customer assigned to the route is served. The goal is to determine the minimum number of vehicles that are required to service all customers with the minimum distribution cost.

The proposed methodology is a multi-start hybrid metaheuristic method which employs Greedy Randomized Adaptive Search Procedures (GRASP) (Feo and Resende, 1995) for diversification and Reactive Variable Neighborhood Descent (ReVND) for intensification local search. GRASP offers an iterative multi-start solution framework which combines greedy heuristics, randomization and local search. The GRASP greedy randomization mechanism is characterized by a dynamic constructive heuristic and randomization. Initially, a solution is constructed iteratively by adding a new element to the partial incomplete solution. All elements are ordered in a list, called restricted candidate list (RCL) composed of the λ highest quality elements, with respect to an adaptive greedy function. The probabilistic component is determined by randomly choosing one of the best element in the list, but not necessary the top of the list. Subsequently, the feasible solution found at each iteration is subject to local search. The overall procedure is repeated until some termination conditions are met.

<u>GRASP-ReVND</u>
While termination conditions not met **Do** $s \leftarrow \emptyset$
  While all customers are served by vehicles **Do**
    $RCL_\lambda \leftarrow$ BuildRestrictedCandidateList(s)
    $x \leftarrow$ SelectElementAtRandom (RCL_λ)
    $s \leftarrow s \cup \{x\}$
    UpdateGreedyFunction(s)
  EndWhile
  RouteElimination(s)
  ReVND(s)
  UpdateBestSolution(s, *elite*)
EndWhile

The proposed GRASP construction phase adopts the sequential construction heuristic proposed in Repoussis et al. (2006). More specifically, a look-ahead capability is incorporated by examining the effect that the selection for insertion of a customer may have on other customers that have not yet been routed. The look-ahead property states that at each iteration of construction, a customer is selected for insertion into a route by minimizing a function that combines, through appropriate weights, travel times-distances and time window utilization criteria. By doing so, it achieves small inter-customer distances within the routes and retains flexibility for subsequent customers to meet their own time window constraints.

Having constructed an initial solution, a route elimination procedure based on ejection chains (EC) as proposed by Bräysy (2003), is applied in order to reduce the number of vehicle routes. The basic idea when using EC for route elimination is the following. Consider a solution s and remove a customer i from a route r_k, where $r_k \in s$. If non-feasible insertion–relocation positions can be found for customer i considering all $r \in s$, $r \neq r_k$, the ejection chain is applied. An ejection chain implies the following: find a route r_m in which if a customer j is removed from r_m, customer i can be feasibly inserted into r_m. Subsequently, this procedure is repeated considering the removed from r_m customer j. The removals and insertions are repeated until the customer examined for insertion can be inserted into a route without ejecting another customer.

Finally, a Variable Neighborhood Descent (VND) metaheuristic algorithm is applied for distance minimization. VND applies a strategy based on the dynamically changing of neighborhood structures (Hansen and MladenovićN, 2002). At the initialization step, a set of neighborhood structures with increasing cardinality ($|N_1| < |N_2| \cdots |N_{\gamma_{max}}|$) is defined. Given an initial solution s, the neighborhood index γ is initialized and the algorithm performs an exploration of the solution space for each neighborhood structure. At each iteration, a best improvement local search is applied until a local minimum is found. If $f(s') < f(s)$ s is replaced by s' and the algorithm continues. Otherwise, γ is incremented (moving phase). The process of changing neighborhoods with increasing cardinality, in case of no improvements, corresponds to diversification of the search close to the incumbent solution, since the neighborhood structure defines the topology of the search landscape.

The above VND scheme is repeated until all neighborhood structures are examined, i.e., $\gamma = \gamma_{\max}$, and no further improvement can be obtained. At this point, the best solution found s is stored ($\hat{s} \leftarrow s$), and a solution reformation mechanism is applied. To this end, the neighborhood index is re-initialized and VND restarts from the reformed solution s until no further improvement can be obtained. Finally, the new local optimum solution s, found after applying solution reformation, is compared to $\hat{s}$ (local optimum solution found prior to solution reformation). If $f(\hat{s}) > f(s)$ $\hat{s}$ is replaced by s and VND is repeated from a new solution reformation. Otherwise, the overall scheme terminates, s is replaced by $\hat{s}$, the best overall solution found is updated and the VND starts from a new initial solution.

<u>Reactive Variable Neighborhood Descent</u>
Given a solution s and a set of neighborhood structures N_γ, $\gamma = 1, 2, \ldots, \gamma_{\max}$
$\gamma \leftarrow 1$, *done* $\leftarrow$ False, *Reform* $\leftarrow$ False
While ($\gamma \leqslant \gamma_{\max}$) AND (*done* = False) **do**
  $s' \leftarrow$ FindBestNeighbor ($s' \in N_\gamma(s)$) "Local Search phase"
  If ($f(s') < f(s)$) **then** $s \leftarrow s'$, $\gamma \leftarrow 1$ "Move phase"
  Else
    If ($\gamma < \gamma_{\max}$) **then** $\gamma \leftarrow \gamma + 1$ "Move phase"

Else
  If ($Reform$ = False) **then** "Reformation phase"
  $Reform \leftarrow$ True, $\gamma \leftarrow 1$, $\hat{s} \leftarrow s$, $s \leftarrow$ Reformation (s)
Else
  If ($f(s) < f(\hat{s})$) **then** "Reformation phase"
    $\gamma \leftarrow 1$, $\hat{s} \leftarrow s$, $s \leftarrow$ Reformation (s)
  Else
    $done \leftarrow$ True
  Endif
Endif
Endif
Endif
Endwhile
UpdateBestFoundSolution (s)

The objective of the solution reformation mechanism is to ruin-and-recreate a current local optimum solution in order to diversify the search and escape, in the long term, from the current local optimum using the accumulated experience acquired during the search. Assuming that good quality solutions share some common characteristics, the basic idea of the solution reformation is to maintain some favorable features and reconstruct part of the solution considered. In case the current solution is local optimum with respect to VND, it is reasonable to expect that restarting from the reformed solution, a higher quality solution may be reached.

The proposed solution reformation consists of two mechanisms. The first identifies which parts (routes in particular) should be maintained and the second mechanism reconstructs from scratch the routes that are candidates for reformation. Let s denote the current solution. The first task is to identify the route r_p with the maximum waiting time. Then, the neighboring routes r_n are defined, $r_n \in N_r(r_p)$. A route r_n is regarded as neighboring to r_p if the customers serviced by r_n, are geographically close to the customers that belong to r_p. In order to measure the extent to which the customers of two particular routes are geographically close, the maximum distance $\max_{(i \in r_n, j \in r_p)} D_{ij}$ among all possible pairs of customers (i,j) must not exceed a predefined limit for closeness v. Finally, all customers of routes r_n, such that $r_n \in N(r_p)$, along with customers of r_p, are extracted from the solution s. The second task is to reconstruct the ruined part of solution s. For this purpose, the aforementioned construction heuristic is employed.

3.5.3. Parameter Settings

Several experiments were conducted both on benchmark data sets and real life data sets in order to determine the algorithmic setup or similarly the parameter settings of the proposed solution methodologies. Towards this end, the methodology proposed for the WLO Collection Problem has a fairly simple structure involving only a single parameter for tuning. The major advantage of LBTA is that the size of the list is insensitive to the characteristics of the problem considered. More specifically, the list serves as a memory of the variability of local objective functions values stored in a form of value changes from its old configuration, while the storage scheme employs up to M values in a binary tree list (Tarantilis et al., 2004a).

On the other hand, the solution methodology proposed for the lubricant distribution problem involves several parameters mainly due to the time window constraints. To this end, the construction heuristic proposed by Repoussis et al. (2006) incorporated four interrelated parameters. Following their sensitivity analysis, conducted on large scale data sets, several parameter value ranges were determined. In the implementation proposed herein these ranges were used for tuning the construction parameters. Furthermore, the overall GRASP-ReVND solution framework incorporates parameter λ and v as described above. The value that best fits the randomized greedy construction parameter λ is close to 10, while the geographical limit for closeness v used by the solution reformation mechanism is set equal to 40. Finally, both LBTA and GRASP-ReVND employed well-known intra- and inter-route neighborhood structures, such as 1–1 exchange, 0–1 relocation and 2-Opt, while the termination condition bounded the allowed computational time consumption up to 2000 s.

3.6. Waste Monitoring Application

The Waste Monitoring Application module provides online information for the exact location and the path followed by each collection vehicle via GPS. Furthermore, it provides data concerning waste level and accumulation rates at selected major collection points and all intermediate storage facilities (accumulation points). In particular, Waste Monitoring Application consists of two parts: the back and the front end. At the back end the user can manipulate and define all associate data of collection points, vehicles, accumulation points and setup user privileges and access rights. On the other hand, at the front end the user is given various capabilities in order to:

- View the collection points and the vehicles of each accumulation point.
- Monitor on line all control variables (availability, fill rate, storage levels and other data) of selected major collection points and accumulation points.
- Monitor on line the content per compartment, the exact position and the status (motion, speed, engine status, etc.) of each vehicle.
- Generate reports per vehicle or per accumulation point for particular periods and compare historical, planned and actual data.

The Waste Monitoring Application ensures continuous monitoring of all stages of WLO collection. This leads to better control over all actors participating the collection processes (e.g. routes followed by the drivers). Furthermore, any variations in WLO quantity carried by a collection vehicle can be diagnosed on-the-fly. Therefore, the scheduler (see Fig. 11) can immediately detect any illegal acts (e.g. selling WLO as cheap oil substitute) or any environmental danger (e.g. leaks). Although the equipment used increased significantly the overall cost of the proposed DSS, its implementation improved visibility and ensured the smooth operation of production. Finally, an additional functionality of the Waste Monitoring Application is a tool for generating reports (see Fig. 12). In particular, the user can generate reports and reporting sheets per vehicle or per accumulation point for particular periods and compare historical, planned and actual data. The latter can improve the overall system performance and allow the decision makers to detect any operational bottlenecks.

3.7. System architecture

The DSS is developed using a multi-tier web architecture that enables sharing of information and algorithms among multiple sites, along with wireless telecommunication facilities which combined GPS for vehicle positioning and GPRS for wireless data transmission. The web application was built using the most recent standards of Microsoft Visual Studio .NET Integrated Development Environment, and particularly, ASP.NET for developing the distributed services and applications. Furthermore, it has an enabled SQL database and uses ADO.NET to manipulate the data through stored procedures.

In terms of system architecture, the well-known server-based computing model was followed. The fundamental three elements of the server-based computing model are multi-user operating system, efficient computing technology and centralized application and client management (Furth et al., 2000). Multi-user operating system allows multiple concurrent users to run applications in separate, protected sessions on a single server. Such application access clients are usually referred as "thin" clients and are characterized by limited computation and remote command capabilities to the server side application concentrated at the service back end. As a result, application performance is not dependent on network bandwidth. Centralized application and client management allows efficient solution of application management, access, performance, and security (Furth et al., 2000). Therefore, in server-based computing all applications and data are managed, supported and executed on separate servers.

To take advantage of server-based computing model a multiple tier architecture is followed, based on reliable data flow, application multi-identity, shared back end computing and legacy application integration. As illustrated in Fig. 13 the proposed architecture consists of four tiers offering both functionality and flexibility in such a heterogeneous web-based environment. At the presentation level (front-end tier), the client views Web forms and all static Web pages for information as well as for a variety of application services, where client users work only with applications' interfaces. At the second level, content tier, a Web server provides interactive view and supports client-initiated transactions with particular access privileges, ensuring the secure and smooth publication of information. Furthermore, a GIS server provides on request all necessary graphical displays. At the third level, application tier (business logic), there is an application server farm, which is used to find requested data and services, makes them available for viewing, and carries out transactions. Finally, at

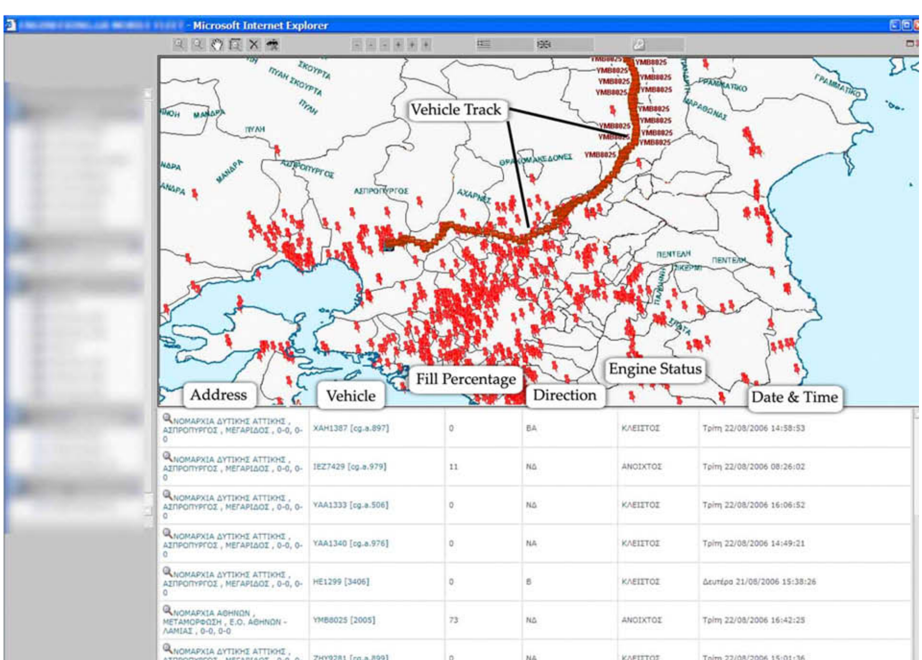


Fig. 11. FMS on line monitoring console.

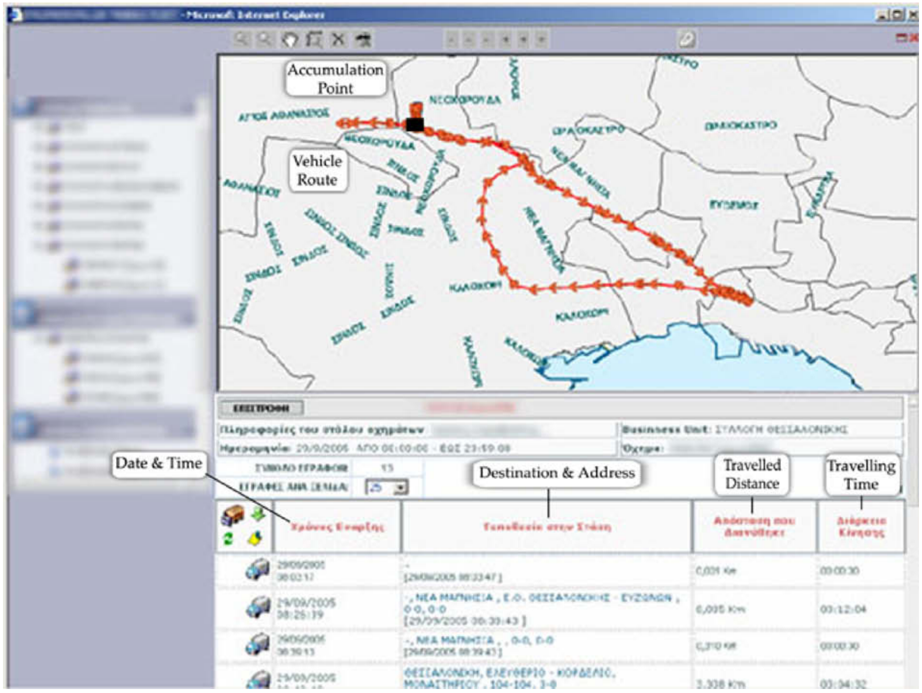


Fig. 12. FMS reporting console.

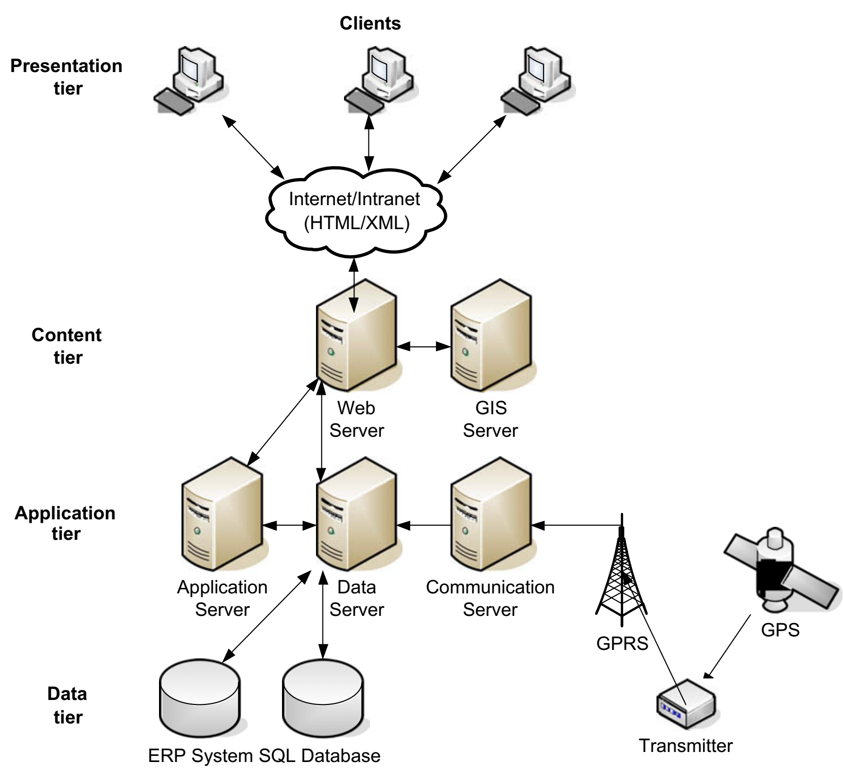


Fig. 13. System architecture.

the forth level, data tier, there is a variety of data and services accessible by the application server.

As mentioned above, the proposed architecture is characterized by concentration of all computing and data intensive prolepses at the back, allowing applications to reside and execute on an application server farm. The latter is a group of application servers, namely Application, Data and Communication servers, that are linked together as a single system to provide centralized administration and scalability. The Communication server is responsible to decode, store and organize the data collected through the corresponding Data server. In particular, each vehicle is equipped with a number of sensors including level gauges and a GPS receiver. Similarly, each accumulation point and selected major collection points are also equipped with level gauges. The above equipment records continuously the status of these data, while it is connected to a controller–transmitter that utilizes the cellular telephony infrastructure to transmit them over GPRS. On the other hand, the Data server manages the flow of data and is capable of performing various functions including accepting input, identifying data owners, importing data, creating logs for tracking and reporting, cashing and mirroring for disaster readiness reasons, among others. Finally, the application server provides all application services supporting also multiple identity capability which allows different users to use the shared computing and data resources with different setup and user's profile.

4. Practical Application

4.1. Motivation

According to the European Union (EU) directive 75/439/EEC[1], all countries members are obliged, whenever possible, to collect and regenerate WLO in an effort to ensure environmental protection and public health. Despite the environmental consequences, historical data indicates that WLO collection and regeneration in Greece is performed at the lowest rate within EU-15 (see Table 1). However, it is worth mentioning that Greece has one of the largest production over consumption rates. Therefore, the strict EU directive and the recent changes in the Greek legislation concerning WLO collection, led to the need of an efficient way to plan, execute and monitor both WLO collection and regeneration operations at the national level. The project was undertaken by the Athens University of Economics & Business and the sole company performing large scale WLO regeneration in Greece (mentioned as the case company thereafter). The outcome of this project was a web-based DSS which facilitates the efficient and effective management of the overall WLO collection and recycling operations.

4.2. User characteristics & Project specifications

The case company produces, recycles and trades lubricants for several purposes and applications including maritime, automobiles, hydraulic systems and other industrial uses. Furthermore, it trades fossil fuels and produces heavy grade mineral oils. Its infrastructure consists of 180 gas stations, a regeneration plant, a lubricant production plant and several storage facilities. Currently its aggregate regeneration capacity (year 2005) reached approximately 40,000 MT, however, this figure is planned to expand in the following years, due to the anticipated increase of the available WLO after the systematic collection planning and monitoring, as proposed by the DSS (see Fig. 14a and b).

Table 1
Lubricant consumption, production and regeneration balance (2002)

	Consumption	Production		Collection	
	A (MT)	B (MT)	B/A (%)	C (MT)	C/B (%)
Greece	140,000	85,000	61	30,000	35
EU-15	4,820,130	2,211,329	46	1,739,044	80

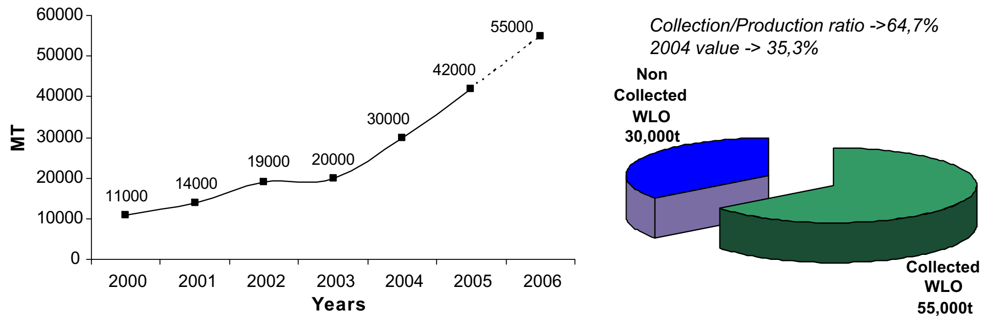
Prior to the realization of the project, the case company infrastructure was far below the anticipated, counting 32 local area collection vehicles with capacities varying from 4 to 7 m^3 and three wide area transfer vehicles with 30 m^3 average capacity, which mainly served the three largest accumulation points and selected major collection points. Since then, the case company has launched a systematic tracing and registration of both minor and major collection points all over the regional terrain of Greece, and gradually expanded its accumulation points network and their available resources.

The anticipated accumulation points network characteristics and specifications for the period 2006-2008 are those shown in (Table 2). The first column of (Table 2) corresponds to accumulation points while the second and third columns to the fleet of collection vehicles and the total available vehicle capacity (TVC). The remaining columns show the total number of collection points assigned, the distance from the central accumulation point (DC), the total estimated turnover amount of WLO collected per year (CQ) and the maximum available storage capacity (SC) for each accumulation point, respectively. Furthermore, it is estimated that the number of wide area transfer vehicles (3rd collection stage) will increase to 6, when the overall network will be fully operational.

To-date the DSS provides online monitoring for the central accumulation point and five major accumulation points, while outputs collection plans for all collection stages and the respective accumulation points. As already mentioned, prior to the DSS application, the collection processes were performed in an ad-hoc basis with drivers deciding which collection points to serve. Moreover, the case company estimated that a large proportion of the collected WLO was being sold as a cheap oil substitute, since there was no control on any illegal activities from the drivers and no estimates of the actual availability of WLO at collection points. It is worth mentioning that 75% of the available WLO for the year 2003 was not regenerated, but instead, it was mainly sold as oil substitute. This figure was reduced to 65% and 50% for the years 2004 and 2005, respectively, after the application of the proposed DSS.

The use of WLO as fuel entails extensive environmental burden with emission of cancerigenic gases and heavy metals. Moreover, apart from the public health consequences,

[1] http://www.raceagainstwaste.com/learn/eulegislation/75-439-eec/.



(a) Collected WLO Quantities (b) National Target 2006

Fig. 14. History of WLO collection efficiency.

Table 2
Accumulation points network specifications (2006–2007)

Accumulation point	Vehicle fleet	TVC (m^3)	Collection points	DC (km)	CQ (MT)	SC (MT)
Central accumulation point						
Athens	24	138.6	8150	–	26,300	4000
Intermediate accumulation points						
Thessaloniki	9	48.3	2,450	508	8700	400
Patra	5	24.2	900	213	4010	400
Larissa	4	21.1	760	316	3800	200
Kozani	2	11.2	350	497	1900	200
Iraklio	3	16.3	480	–	1730	200
Kavala	3	16.1	460	671	1600	200
Chania	2	11.2	380	–	960	100
Livadia	2	11.1	290	118	1400	100
Ioannina	2	10.9	310	435	940	100
Preveza	2	10.9	330	370	1220	200
Xanthi	2	10.9	300	727	840	200
Tripoli	3	16.1	380	285	1600	100
Total	63	347	15,540	–	55,000	6500

the result of the illicit trading was lack of collected WLO, which in turn resulted in lack of basic lubricants needed for the production of lubricant products. Consequently, the case company not only had to import 15,000 MT of WLO from other countries (in order to assure the continuous operation of the regeneration plant) but to procure 10,000 MT of basic lubricants as well, which resulted in a significant financial cost.

4.3. Realization phase

The realization phase of the project was critical, and affected significantly both the design and specifications of the DSS. During that period, the effort mainly focused on performing a systematic tracing and registration of collection points. At the first level, there was a need to validate and verify their addresses and their actual geographic coordinates. Figs. 15 and 16 show the locations of collection points over the urban road networks of two large Greek cities i.e. Thessaloniki and Patra. At the second level, the collection points database was populated with all control variables for each collection point, in order to maintain historical data. This task was important since it affected directly planning specifications, i.e., estimation of travel times or available WLO quantity. Based on historical data, the collection points were classified either as minor or major, and these that would be subject to online monitoring were selected. Table 3 offers an insight of the nature and locations of collection points registered at the responsibility areas of Thesaloniki and Patra accumulation points.

Subsequently, the research focused on analyzing the road network structure, which has peculiarities due to the mountainous terrain and traffic congestion within large cities. Initially, the spatial characteristics of the greater Athens (capital city of Greece) road network were analyzed, in which more than 60% of the overall handling and passage of WLO is performed. The city of Athens covers around 2980 km^2 in an area of which 640 km^2 is build-up environment. The central area is about 12 km^2 and traffic restrictions are applied for passenger vehicles based on odd/even last number of license plates. The transportation infrastructure consists of a road network with total length exceeding 4200 km. Out of these roads, 12% are dual carriages, 28% are one-way streets, 77% of these streets have one lane, 17% have two lanes and 6% have threes per direction. The road network is controlled by approximately 1100 signalized and 210 overpass intersections.

Road transportation in most large cities encounters significant delays due to traffic congestion. Currently, traffic delays increase by 3% yearly in the central areas of Athens, by 3.6% in the rest of the main urban area and by more than 7% within the sub-urban and semi-rural areas. The average speed considered, which is important for acquiring any estimation of travel times, is 23 km/h in the main urban areas, 35 km/h in remote suburbs and 52 km/h in semi-rural areas. It is also worth mentioning that average speeds are changeable subject to the weather conditions. Similar are the observations for the road networks of Thessaloniki (see Fig. 15) and Patra (see Fig. 16). Based on all the aforementioned characteristics, appropriate adjustment weights where assigned to each road segment and the knowledge base was built up accordingly.

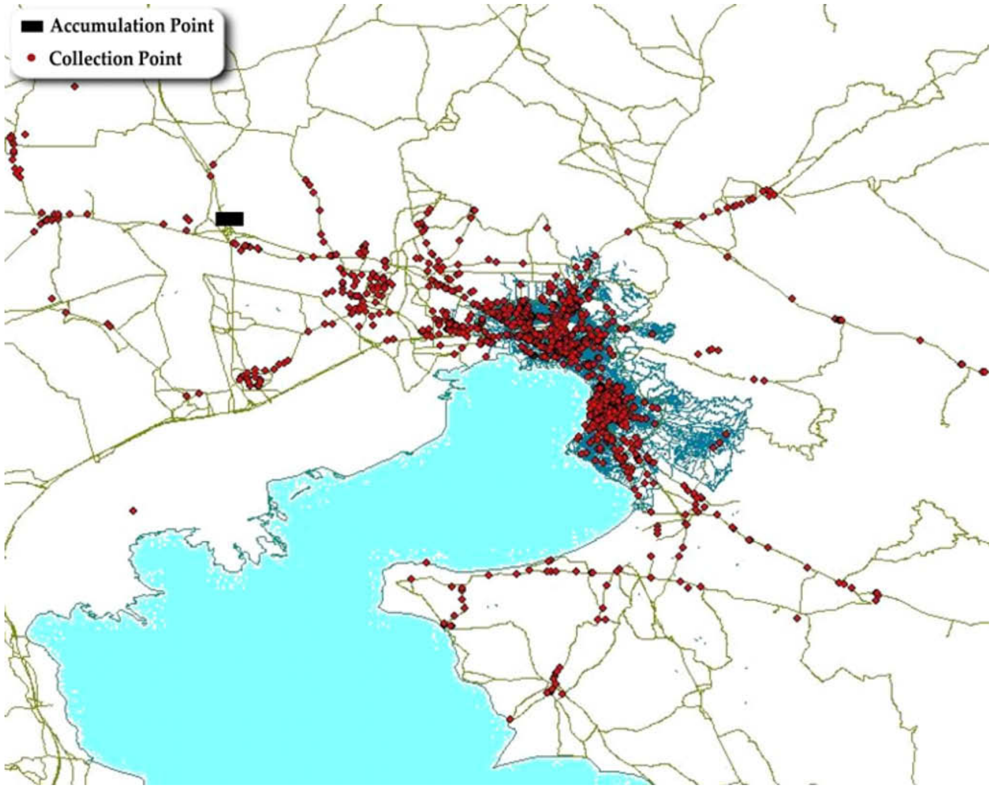


Fig. 15. Accumulation point of Thessaloniki.

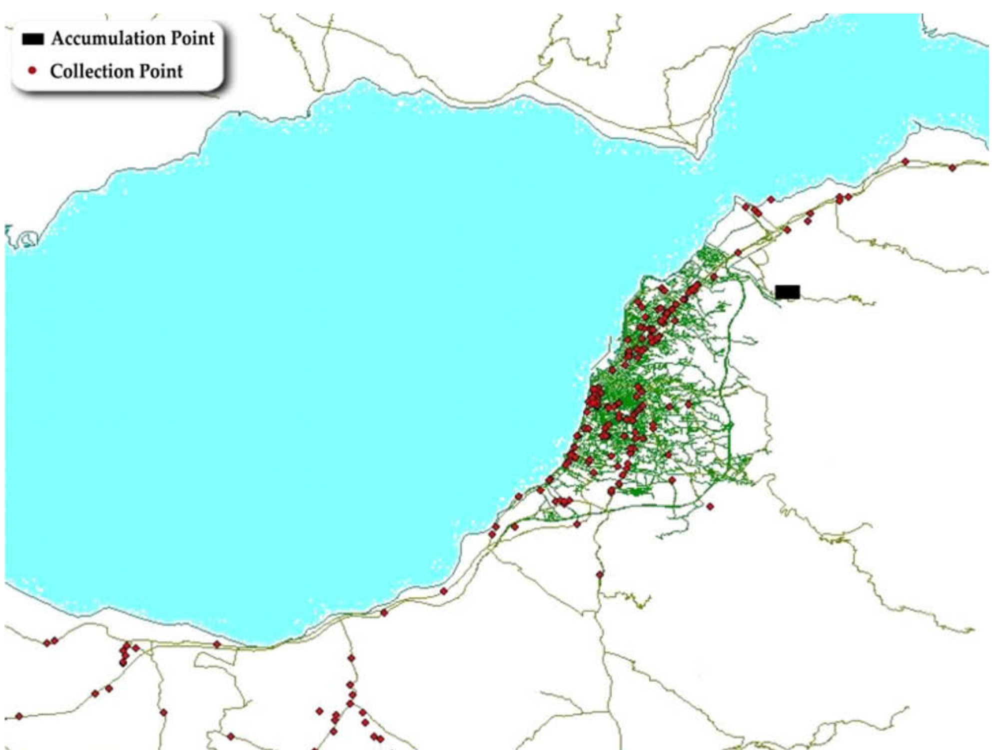


Fig. 16. Accumulation point of Patra.

Table 3
Nature of collection points at accumulation points of Thesaloniki & Patra

Nature of collection points	Thesaloniki		Patra	
	Urban districts	Greater area	Urban districts	Greater area
Automobile workshops	629	535	70	170
Heavy track workshops	6	5	7	17
Gas stations	364	309	78	190
Industries	117	99	27	66
Other	137	116	53	129
Cars sales agencies	67	57	17	42
Building/industrial sites	3	5	10	25
Total	1323	1127	262	638

4.4. System evaluation & Expected results

Since the pilot application of the proposed DSS, the system found to comply with all specifications posed and configured during the Needs Analysis, the Business Integration Planning sessions and the Mission and Vision statements. During the implementation phases of the proposed DSS (see also Fig. 17), various experiments and evaluation tests were conducted. Furthermore, in order to ensure the seamless functionality and operational effectiveness of the proposed DSS, detailed auditing was conducted to every software functionality, to every module of the system as well as to every supportive technology used. The components of the evaluation process are described as follows:

– Evaluation of manageability: involves the occupation of users with the DSS, along with the recording of their reactions and opinions about the functionality and the usage of the system.
– Evaluation of operations: it is a process of identifying any declination between the predetermined specifications of the proposed DSS and its actual functionality.
– Evaluation of the system: involves the examination of the DSS final specifications with respect to the Needs Analysis and Mission and Vision statements.
– Evaluation of acceptance: process of comparing the delivered DSS with the actual needs of the final users.

The main steps followed to evaluate the proposed DSS involved the design of the evaluation tools and processes, the generation of evaluation scenarios, the implementation team selection and evaluation scenarios application, the identification of acceptance problems and final delivery of the system software.

The results emerge from the exploitation of the proposed DSS are multi-dimensional and ultimately target productivity and competitiveness enhancements. The latter is enabled through the development of innovative business

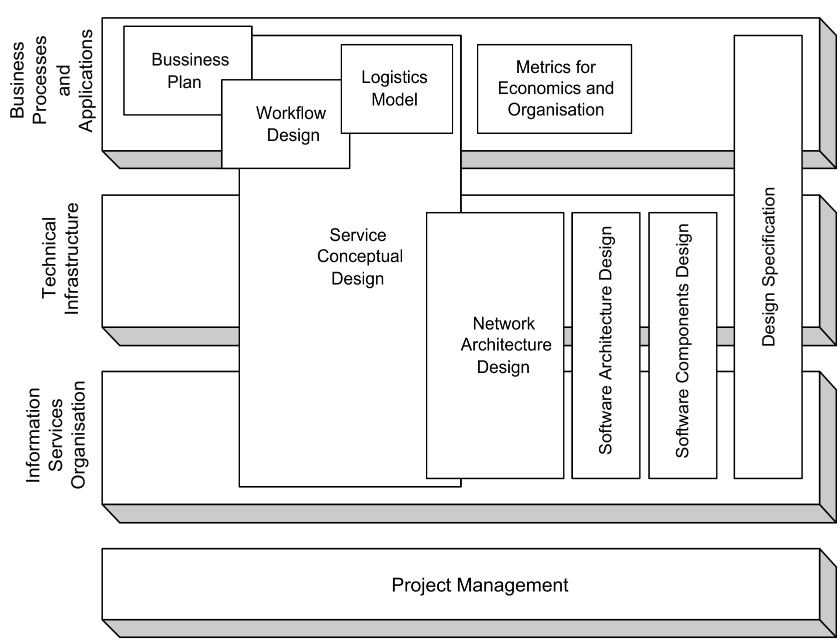


Fig. 17. Project phases.

processes for the strategic planning and operation of the company's most novel market (waste recycling), which decreases waste collection costs, increases waste collection capacity and recycling potential, enhances customer relations and advances human resource capabilities and competencies. The proposed DSS mainly addresses the following core target sectors:

– Development of enterprise wide end-to-end Information Systems, using web technology which incorporates wireless telecommunication facilities, sophisticated optimization methods, decision support tools, monitoring and reporting functionalities and seamless ERP integration.
– Development and optimization of business-to-business relationships, via the direct information sharing and reverse production planning and scheduling of the waste collection chain.
– Development of innovative business processes and policies, especially concerning the closed-loop supply chain design from waste collection to distribution of lubricant products to customers.

4.5. Immediate Benefits

The immediate benefits emerged from the application of the proposed DSS showed significant improvements to all cost and collection efficiency measures. For privacy reasons, the data provided below are appropriately masked. Table 4 presents cost and performance measure of the 1st collection stage for selected periods prior and after the application. In particular, the first column shows the total amount of WLO collected, while the second and the third columns refer to the aggregate collection cost and the associated unit cost per WLO collected. The forth and fifth columns refer to the total number of vehicles participating in the daily collection operations and the average vehicles' capacity utilization.

In all periods, a considerable increase is observed in terms of collected WLO with a simultaneous decrease in all fleet cost measures. The latter is reflected on both aggregate fleet costs and unit fleet costs, which further decreased. In particular, during the second half of 2004 a 24.6% reduction, was achieved with respect to the average cost per unit transferred. Moreover, it is also worth indicating that the latter figure further decreased by 9.2% (see periods 2004B and after) because the number of collection points with online monitoring increased, while the users have passed a familiarization period using the planning tools. On the other hand, the relative reductions to the overall collection costs and the continuous increase observed in terms of capacity utilization shows the efficiency of the vehicle routing plans produced by the DSS.

Similar are the figures obtained (see Table 5) for the major accumulation points of Thessaloniki and Patra. In particular, for the periods following DSS application, the cost reductions obtained reached approximately 30% and 28%, in terms of unit cost, respectively. Especially, for the Thessaloniki accumulation point, cost reductions followed significant increments with respect to vehicles average capacity utilization. Contrary, for the Patra accumulation point, the latter figure remained on average the same. However, this was expected since the service area covered is larger, while the available WLO capacity is significantly smaller and the dispersion among collection points is larger. Therefore, the long traveling times dictate the sequence of collection points visited by vehicles. Similar are the results obtained for the remaining accumulation points. Table 6 provides the aggregate results obtained from all collection stages.

Furthermore, it is worth noting that the cost reduction observed is attributed either to the use of sophisticated

Table 4
First collection stage fleet costs

Period	WLO collected	Collection cost	Unit cost	Available fleet	Utilization (%)
Central accumulation point					
2004A[a]	6038	115,750	19.17	14	61.88
2004B	7213	104,175	14.44	14	73.92
2005A	9564	125,258	13.10	18	76.24
2005B	9498	125,187	13.18	18	75.71

[a] Periods prior DSS.

Table 5
Second collection stage fleet costs – Thessaloniki & Patra

Period	WLO collected	Distribution cost	Unit cost	Available fleet	Utilization (%)
Thessaloniki accumulation point					
2004A[a]	2547	50,576	19.86	6	60.91
2004B[a]	2564	49,865	19.45	6	61.31
2005A	3594	48,752	13.56	7	73.67
2005B	3603	48,957	13.59	7	73.85
Patra accumulation point					
2004A[a]	894	19,692	22.03	2	64.14
2004B[a]	910	19,743	21.70	2	65.28
2005A	1329	21,053	15.84	3	63.56
2005B	1398	21,187	15.16	3	66.86

[a] Periods prior DSS.

Table 6
Aggregate WLO collection results

Period	WLO collected	Distribution cost	Unit cost	Available fleet	Utilization (%)
First collection stage					
2004[a]	13,251	219,925	16.60	14	67.90
2005	19,062	250,445	13.14	18	75.97
Second collection stage					
2004[b]	16,749	335,764	20.05	20	60.08
2005	22,938	324,219	14.13	24	68.57
Third collection stage					
2004[b]	16,500	39,325	2.38	3	72.34
2005	22,600	53,256	2.36	4	74.31

[a] 2004A prior DSS.
[b] Periods prior DSS.

vehicle routing algorithms, which provided minimum cost routes with high vehicle utilization levels, or to the use of the waste monitoring application and maintenance of historical data which reduced illicit trade. The latter tools enabled schedulers to manage effectively the fleet of vehicles that participated in the collection operations, providing them real time assistance, turn by turn navigation and trace of any deviation from the scheduled routes.

On the other hand, it is important to evaluate the estimates provided by the DSS in terms of WLO availability, which are further used to model collection points service urgency and to predict the planned collected quantities. During 2004 monitoring was provided only by a very small portion of major collection points, and thereafter, collection planning for the 1st collection stage was performed mostly based on historical data. It is interesting to examine whether the increased accuracy of the data available in 2005 (due to the installation of tank level gauges to a large number of collection points) is reflected on the results acquired in 2004. In particular, the average deviation between planned and actually collected quantities for 2004 were up to 10.2% which further decreased to 5.0%. The latter figure is satisfactory and indicates that there is no need to expand further the online monitoring infrastructure.

Finally, visual are the benefits gained with respect to the distribution management of lubricants end-item products to customers. On time delivery of products at customers' locations is of primary importance since it constitutes a large portion of the company's logistics costs and determines to a large extent the quality of service provided. Since the implementation of the proposed DSS, the quality delivered to the customers was improved. In particular, due to the efficient and effective routing plans produced, on time customer service and delivery at most cases achieved. Furthermore, 12% reduction of the operational costs were observed, since the vehicle routes generated minimized the total number of hired vehicles and the associated distance traveled.

5. Conclusions

This paper presented the systemic dimension and the modular architecture of a web-based DSS that uses sophisticated optimization methods to manage effectively reverse logistical planning problems. The DSS is developed using web technology that allowed sharing of information and algorithms. The focus was on developing the appropriate planning tools that enable a WLO regeneration company to improve substantially and monitor effectively the overall performance of its production and collection. The application of the DSS to an actual industrial environment improved productivity and competitiveness and is currently used by the sole WLO regeneration company in Greece. In particular, reductions up to 25% and 30% were achieved with respect to the cost per unit transferred by the collection vehicles. Similar are the figures for the efficiency and effectiveness of lubricant distribution operations to customers.

The web-based DSS mainly incorporated intra-city vehicle routing with real-life operational constraints, while integration with an ERP system allowed utilization of functional modules and combination with other planning tools. Furthermore, the DSS provided on-line monitoring and reporting to all waste collection stages. All the above properties replaced and optimized to, the extent possible, a number of labor intensive processes and helped the case study company to support group decision making and achieve several organization goals allowing the sharing of information and tools among multiple users. Additional benefits associated with the regionalized–centralized system architecture are also identifiable. More specifically, the system enforces modular architecture and component re-usability. The latter allows development of tools which can be used by other applications, and therefore, avoiding possible duplication of functionality and reducing development costs of future applications.

In terms of future benefits it is expected that the competitiveness of the case company will increase, since logistics costs will decrease by a large percentage, and the consumer supplier interaction will be enhanced. On the other hand, the productivity will increase, due to effective and efficient management and monitoring of all stages of the supply chain.

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