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A GENERALIZED SIMULATION FRAMEWORK TO MANAGE LOGISTICS SYSTEMS: A CASE STUDY IN WASTE MANAGEMENT AND ENVIRONMENTAL PROTECTION

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ABSTRACT

This paper presents an innovative modeling framework able to support planning, management and optimization of waste collection operations in an urban context. A proprietary simulator composed by three functionality modules (Global Positioning System, Data Mining system, Simulator for routing and resource exploitation) was implemented by the authors, and was then validated on a specific set of case studies. This application has been made possible within PLANAGO regional government funded research project and was based on previous experiences of the authors. This approach was also extended beyond the particular application and is now under test in different application fields strictly related to logistics and environmental protection.

1 INTRODUCTION

The optimization of the logistics of the refuse collection service in a large metropolitan area is a complex example of transportation logistics problem. Several performance drivers are to be decided upon in the formulation of a feasible and cost-effective collection plan. The efficient allocation of a specific vehicle type to a collection route on a given work-shift is highly dependent not only on the expected performance of such an allocation, but also on the implications that this choice may have on the performance of all the remaining vehicle-route pairs. These interdependencies are mainly due to the fact that the number of available vehicles per vehicle type is limited and, therefore, the allocation of a first-choice vehicle (e.g., the most efficient one) to a route may leave second or third choice vehicles available for allocation to other collection routes. In such a sense the optimization of the process at the individual route level is likely to produce a resource allocation plan which is sub-optimal from the perspective of the refuse collection service as a whole. Simulation-based testing is the only approach by which each resource allocation scenario can be thoroughly tested taking into account primary, secondary, and tertiary impacts of each allocation choice on the performance of the whole service over the 24 hours.

In some big towns especially of southern Italy (i.e., Naples), the capacity of disposal and recycling waste has been a critical issue for a long time, and the necessity of differential waste collection led to an increase of number of collection resources, with trucks and other specialist means to be bought, and an increase in number of collection points being deemed mandatory. These changes need to be matched with

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traffic conditions, physical constraints in terms of routing and accessibility, and the necessity of a high service level anyway, since it's not possible to leave waste unattended for days in front of houses or public places. Hence the need of a simulation tool able to support decision making for such a topic. It's not the first time that authors faces such problem with a simulator, but in this new generation system a generalized approach has been proposed leading many more functionalities (i.e., GIS integration, resource allocation, scalable approach, etc.).

2 ADOPTING A SUITABLE MODELING APPROACH

2.1 A generalized model

One of the critical aspect of the modeling of a complex logistics system is related to the particular nature of the process that could be summarized in two main categories:

1. First category is a class of process that if interrupted, resume at the same point where they were stopped. In this category are loading and unloading operations, deliveries, picking and similar activities.
2. Second category is a class of operation that if interrupted, resume from the beginning and not at the point they were interrupted. Examples of such operations are clearance procedures, safety procedures and similar.

In order to explain this point a more complex example from Briano et al. (2010a) is considered that involves a LNG tanker docking at a LNG terminal for loading and unloading operations.

The layers are described through the dynamics system and involve the ports, the ships at sea, and the ships in the port. The first layer involves all the ports mainly to check parking availability, so a system with number of the ports as dimension is modeled. The second layer involves the ships and their cycle phases including: check availability of ship, the possible navigation to homeport, the loading phase, the navigation to destination port, docking at the port, unloading, the re-placement, and finally the ship could be available to start another cycle. Each ship can start and stop its cycle as needed. This layer handles a system with number of ships as the dimension. Finally, the last level is focused on the dynamics of the ship into the port. The steps involved are the entry maneuvers, the landing operations, and the tanks mooring as in Briano et al. (2010b).

Since weather and sea conditions could severely affect the loading and unloading operations the tanker should be ready to promptly undock if sea condition becomes too bad to guarantee the safety level of the operations. Of course if this occurs when part of the loading/unloading has been done the tanker has to resume later from the same point (first category process) while all the docking, security checks and clearance operations have to be repeated completely (second category process). In this approach any operation could be interrupted if certain conditions occur and, according to the category of the operation, a resume condition should be utilized. Based on such assumption where unexpected events may take place any moment, the discrete event paradigm is not considered suitable, instead a time stepped approach is used.

In Figure 1 the general model is presented, in such schema is possible to notice two states: State A and State B, transition from State A to State B is regulated by a condition that is given on the remaining time elapsed on the current state according to a predefined process. When event transition occurs a corresponding time is set over the process to trigger another transition at the end. In the proposed model the system is bouncing cyclically from State A to State B as the successive process times elapse.

In the proposed model this is used to define two conditions that occur during waste collection: in State A the collecting truck is moving along the path to reach the collecting points. Once it reaches the collection point, the picking activity is started consuming the available space on board. Such process continues until a minimum free space remains on the truck. When such limit is reached the truck travels back to unloading point where, after having been emptied, it will resume its collecting path until all the paths have been successfully explored.

This approach has been generalized by the authors transforming the building blocs presented in Figure 1 into vectors. This allows defining a transition matrix that captures the state changes using the same simple model for a wide class of complex modeling.

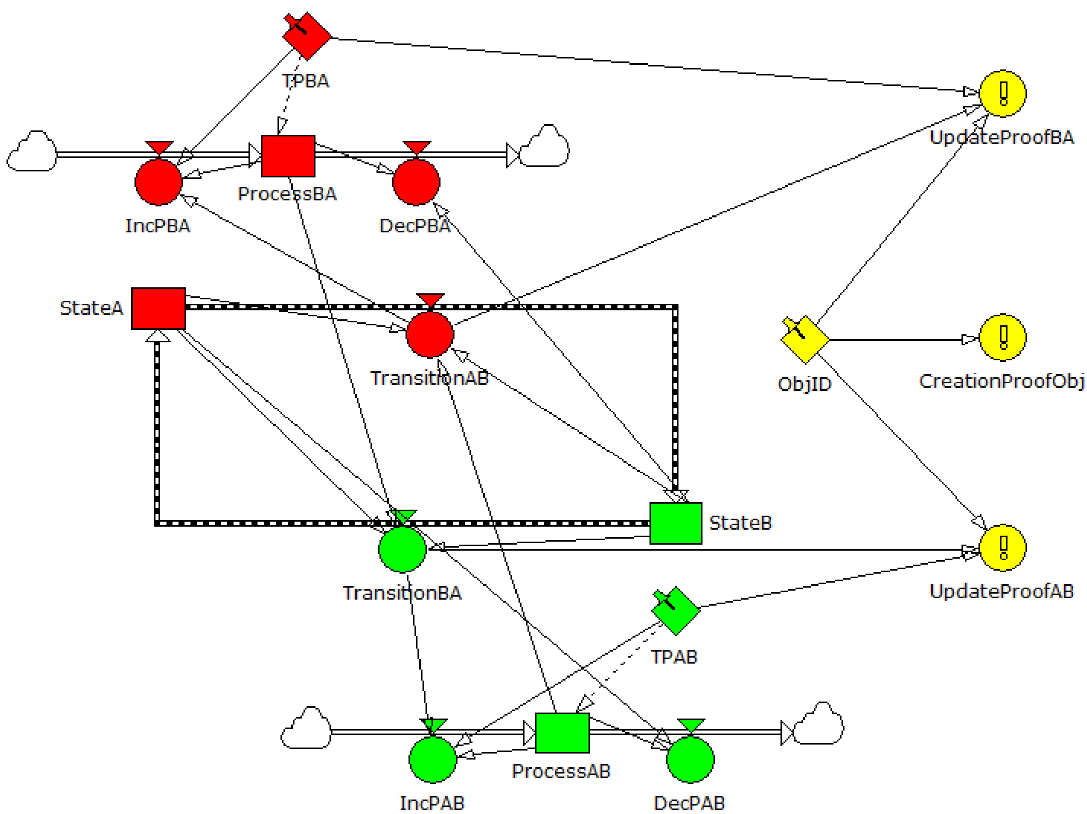

Figure 1: The generalized simulation model

Let's consider as example a vehicle whose task is to collect waste from a set of collecting points (i.e., waste bins) positioned along a specific route, let's suppose this vehicle is in State A (collecting). This route is identified as ordered set of collecting point using some particular algorithm such as Travel Salesman Problem (TSP), Minimal Spanning Tree (MST) or any other suitable heuristics. During its path the vehicle is collecting material from the waste bins encountered on its way resulting in a consumption in its available space. Since the total quantity of waste present in each bin is a stochastic variable (in term of both weight and volume) the saturation level could be reached in a moment that is randomly generated. When enough material has been collected the vehicle cannot go further into its mission and enters State B (repositioning). Starting from the point it has reached it travels to a deposit point where it can unload on board material and then return to the point where it left its route to continue its collecting path, and is again into State A.

Based on this model the entire system could be modeled simply in term of two state transition transitions: collecting and repositioning where geospatial data such as: traveling distance and time, waste bin positions and waste quantities can be obtained from various data sources regardless of the specific logistic configuration of the system.

This leads to a complete generalized approach where model is fixed and the data configure the simulation to the particular application case. In this way is possible to say that this approach is completely data-driven reducing the application of such model to a simple data entry.

Using such a modeling methodology the authors were able to model complex logistics systems well beyond the proposed example using the resulting simulation as the core of a Decision Support System.

2.2 Architectural design

The implemented simulator, developed based on the above model, consists of three macro modules as in Caballini et al. (2010):

- *Geo-referencing roads and attributes through the Simple Object Access Protocol (SOAP) protocol*: The integration with geo-referenced systems using the SOAP protocol, allows accessing GIS (Geographic Information System) support skipping the stage of data entry (or at least drastically reducing it), thus reducing implementation costs. The significant points can still be included (geo-referenced) in the digital map with the aid of GPS ensuring the completeness of the information.
- *Data Mining System on Waste production*: This module uses Data Mining based on Artificial Neural Networks and Polynomial Models of the Second Order. It extracts the data reports and collection of census data (population, non-domestic users, etc.), the map of the relationship between the socio-economic areas and the production of MSW (Municipal Solid Waste). The results are subjected to a thorough statistical analysis (F-test, test R2 Lack of Fit test) and input to the artificial neural networks for determining the response surface (RSM). The forecasting system is thus defined to be more reliable than those currently in the literature and specialized software.
- *Simulation based planning tool*: This module uses a Monte Carlo simulator based on the proposed methodology for MSW collection. The simulator has an optimization module used to create the collection paths based on algorithms and heuristics such as CRVP (capacitated Vehicle Routing Problem) developed at MIT (Massachusetts Institute of Technology). The simulator is designed to simulate the entire process of waste picking.

The entire implementation was made using Java™ integrating with several SOAP Web Services (using Apache Axis Framework) in order to provide support for the geo-localization of the collecting points. A central database was used to provide a repository for data and a way to consolidate data coming from different sources (i.e., waste weighting stations, waste bins RFID, etc.) while the general stochastic model was set using Monte Carlo random variable generation.

2.3 Objective

The general objective for the proposed model was to provide quantitative evaluation of a waste collection plan feasibility. This complex task requires, in fact, an instrument able to simulate the various operations as well as investigate resource requirements and utilization. In order to support this phase a data driven simulation model was implemented in Java™ incorporating the above mentioned methodology. Java™ offers a platform independent, Object Oriented and Multi Threaded environment for building small but complete simulators for optimization problems taking advantage of many ready to use computational packages (i.e., jDisco™ for combined discrete-continuous simulation, JaNet™ for Neural Networks, JDBC™ for database access). In this way the implemented simulation model was connected to an Oracle database designed to provide all the information needed for the simulation.

The simulator is based on a set of 4 main objects as in Giribone, Orsoni, and Revetria (2002):

1. the Graphical User Interface (GUI), providing support for verification and validation (animation, reporting, etc.)
2. the object Point, representing a stop in the collecting path
3. the object Resource, representing a worker or a specific vehicle class
4. the object Vehicle, identifying the various classes of waste collection trucks

The GUI allows users to manually insert garbage picking points on the pre loaded map and define for each point a mean time for the collecting operations. Since this operation should be done point by point and could be really time consuming an automated procedure was designed to help the user. In the automatic point positioning the user will select the starting point, the average operation time per point and a pre-defined point distance, by clicking at the final point the GUI will calculate the total distance between the starting point and the finish point and will position a point at each predefined distance from the starting point assigning to it the pre-defined operation time. The obtained points sequence could be used to update the Point database or directly used for a first tentative simulation.

The point object are organized in a hierarchy in which each point belongs to a Street and a Sequence. The Street is a simple relationship that is used to identify a set of point in the database in order to re-build the sequence at design time; while the sequence is a set of ordered points that are processed one at time during the simulation step.

For each point a resource is required for processing, all the resources are described in the DB Resource table in terms of Vehicle object.

A Vehicle is a class of Resource object describing the total number of resources available and its unavailability rate. The unavailability rate is a ratio defined as follows:

$$1 - Av = \frac{MTTR}{MTBF + MTTR} \tag{1}$$

At each simulation step (one simulated day) the number of resources available is obtained from the Vehicle objects through a Monte Carlo simulation as in Guerra, Murino, and Romano (2009) and then the points are processed for the trip simulation. For each point a sequence is initiated according to the name of the sequence to which the point belongs, if the sequence already exists the considered point is simply added to the sequence; the resource is identified at each point and is associated with the right sequence. At the end of this process a set of sequences with their associated resources will be available; for each sequence the required resource will be assigned based on the resource availability and a new simulation thread will be instantiated. The simulation generation process is shown in Figure 2.

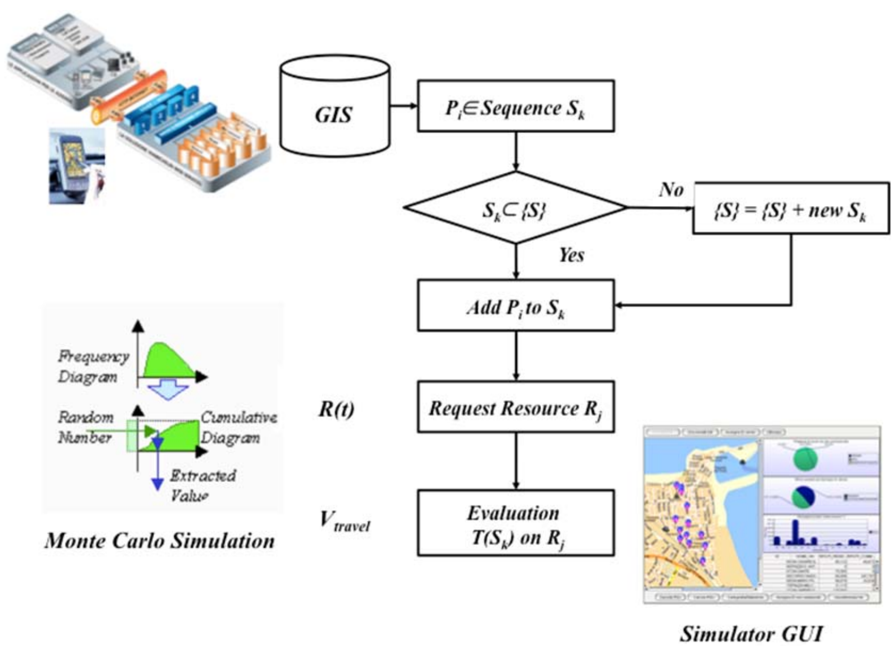

Figure 2: The simulation generation process

The simulation thread will process each point of the sequence by computing the travel time and the operational time as in Cantarella and Sforza (1991); for each of them a Monte Carlo based simulation is performed. For travel time the value is calculated as follows:

$$T_{Travel}^{1\to 2} = \frac{\sqrt{\left(x_2 - x_1\right)^2 + \left(y_2 - y_1\right)^2}}{V_{Travel}} \tag{2}$$

where x_i and y_i are the coordinates of i-th point and V_{Travel} the estimated resource moving speed. The total time spent for a simulated trip will be computed by the formula:

$$T_{Sim} = \sum_{i=1}^{n} T_{Travel}^{i\to i+1} + T_{\Pr ocess}^{i} \tag{3}$$

At the end of the simulation a report file will be available for each sequence with all the simulation details reordered. Since each sequence is a separate thread the graphical representation of the simulation can show multiple pick up vehicle running at the same time. This is very important during Verification and Validation process since the graphical representation of the process is much more realistic with all the vehicle moving at the same time as in Banks et al. (2000).

3 VERIFICATION AND VALIDATION

3.1 Validation of GIS Module

The application allows geo-referencing roads. In particular, it obtains longitude and latitude of each address entered by connecting to the GIS Web server.

The Method called geo-referencing has two different components. The first, given an address, returns the longitude and latitude of the point, taking in account if there is an ambiguous situation (e.g., more addresses corresponding to the selection). In this case, the user must choose the correct one among a list of addresses matching the selection criteria. If nothing is found for the selection criteria, the user can manually insert the parameters. If no street number is given to the system, it will calculate the center of the address inserted. The second component given a file with properly formatted addresses, returns an array of addresses. Each address object array follows the logic described above.

To validate the Geo-referencing module, it was necessary to test the correctness of the assignment of addresses to latitude and longitude. A set of data was taken randomly with some logical points and compared with the results given by a popular worldwide website, giving information on maps and place positioning.

3.2 Validate Data Mining Module

The second module uses a data mining system based on artificial neural networks and second-order polynomial models as mentioned in section 2.2. The module extracts the data reports and collection of census data (population, non-domestic users, etc.), the map of the relationship between the socio-economic areas and the production of MSW. The results are subjected to a thorough statistical analysis (F-test, test R2 Lack of Fit test). If the regression analysis can not find a suitable relationship, it is possible to use neural networks. This neural network method involves an error of approximation typically greater than the statistical method. Before run the regression it is necessary to configure the analysis method.

There is a great number of methodologies aimed at formulating mathematical relationships, more or less complex, between the variables (factors, responses) that determine the behavior of the system. In other words, it's possible to construct a model able to connect the response (waste) to factors (non-domestic and domestic users) involved in the system. In general there is a dependent variable Y (response: MSW produced daily per census box) which depends on k independent variables named X_1, X_2, .., X_k (factors:

Hotels, Shopping Centers, etc.). The relationship between these variables is characterized by a mathematical model called "regression equation."

Operationally it is necessary to identify the type of relationship (linear, nonlinear) that best approximates the system testing the significance and goodness of fit. Indeed since the model is a polynomial expression, whose order is given, it is our task to attempt to verify the correctness of the hypothesis made (order of the polynomial adopted). The tests are performed according to the methodology ANOVA. It remains to observe that the model is built on available data, i.e., the selection of variables influencing the system and the characterization of the study areas (boxes census) were imposed by the availability of these, and so were not determined by an aprioristic design. Therefore this iterative regression approach has been necessary for the test scenarios to find the correct mix of factors able to represent the situation. It is understood that this approach has a high risk of detecting relationships between variables that are not significant in reality.

3.3 Validate the Simulation Based Planner

The optimal location of bins, both for the number and the type, was determined using the methodology proposed in Section 2.2. In particular a preliminary solution was obtained by using Branch & Bound. This algorithm, developed by Land and Doig (1960) starts from the set of all feasible solutions, which is then divided into two sets with empty intersection to summarize the initial set (Branching). For each set a limit not higher than the minor "cost" (defined as objective function to be maximized / minimized) is calculated for each element (bounding). Proceeding in this direction, gradually branching sub sets that contains the best solution, it's possible to reach a set with one element that is a close to optimal solution.

The boundary conditions for the definition of the optimum point are summarized as follows:

- Type of box. Represents the volume of containers to be placed on the ground. There are different types of garbage collection boxes with standard sizes.
- Filling % maximum. Represents the load factor of the box.
- Frequency of collection. Represents the number of collections made weekly. The frequency gives the number of days for which the bins have to buffer the production of MSW. For example, a frequency 3 to 7 (three times a week) means the necessity to have a capacity of containers of 3 days in buffer.
- Maximum Distance allowable between users and the bin. In general, municipal regulations provide for a maximum allowable distance between the house and location of the nearest box.

The output of the method in addition to the collection points (characterized by longitude and latitude, number and type of containers present, utilities served) must also provide a possible list of non-compliant users (typically in relation to the distance) to be managed manually after the optimization as in Guerra, Murino, and Romano (2007).

The validation of the tool for placement was made by considering a sample area comprising two roads with 284 residents. The preliminary solution was passed to the simulator that provided support for robustness investigation and fine tuning. In particular, the simulation was able to introduce resource availability and collection quantity variability over the various missions resulting in a significant modification of the proposed plan.

For the proposed application example, the following variables were considered:

1. Volume of containers. Volumes ranging from 120 liters to 80 liters
2. Frequency of collection. Two possible frequency of collection, six times a week or three times a week.
3. Maximum distance allowable from the box to houses. Varying between 50 meters and 100 meters.

The model was tested on a target city that produces approximately 1000 tons of refuse every day which are disposed of into 15,200 designated collection bins distributed over its greater metropolitan area. The model considered the daily collection of such refuse using a range of six classes of picking vehicles on 130 separate collection paths distributed over 2 possible work shifts. The six classes of collection vehicles correspond to different loading features and tank sizes. Vehicles of different features and tank sizes are allocated to the designated routes taking into account the accessibility constraints imposed by the morphology of the corresponding urban areas: smaller vehicles (tank capacity = 2 m^3) are typically assigned to collection routes passing through the narrow streets, while larger vehicles (tank capacity = 24 m^3) are assigned to less densely built residential areas.

A preliminary statistical analysis conducted on the data provided by the company identified two critical aspects of the "as-is" collection process: a significantly high number of vehicles compared to the number of collection routes (the ratio was approximately 1 for each of the six classes of vehicles), and a correspondingly low vehicle utilization within each class (between 58% and 69%) showing significant margins for improvement. The objective function for the optimization process, connected to the simulation, was set to be the cost of the collection process per kilogram of refuse over the 24-hour collection cycle. Such a cost is inclusive of all the relevant operations, maintenance, and personnel costs for each of the vehicles employed in the daily collection plan. An additional cost which is taken into account is the cost incurred for the trip(s) that each vehicle needs to make to unload the refuse at the discharge site. It is important to notice that the vehicles depart from a main garage located in the vicinity of the discharge site and return to that same site one or more times during the day depending on their capacity. In the choice of the vehicles to be allocated the model consider the fact that the distance between the discharge site and the collection points is often comparable to the entire length of the collection routes, thus favoring the choice of the largest vehicle allowed by route accessibility constraints.

The model produces a first attempt resource allocation plan selecting the vehicle of first choice for each route based on the corresponding collection costs (as defined above) and on the accessibility constraints imposed by the route. Starting from this preliminary resource allocation plan, the heuristics proposes a schedule for the collection activities on the different routes distributing them over the designated work shifts. The scheduling constraints are chiefly related to the number of vehicles available for each class. If the vehicle of first choice is not available for all routes on either work shift, the original plan is not feasible and, thus, a vehicle of second choice is assigned to some of the routes. This process is iterated until a feasible solution of minimum cost is found. The resource allocation plan and schedule proposed by the heuristics module is determined considering only technical feasibility and cost-effectiveness and without considering possible delays due to route interdependencies, vehicle failures, and traffic conditions. The actual feasibility and cost of each solution can be verified through the stochastic simulation module, which explicitly accounts for these performance drivers by associating to each route a probability distribution of delays due to traffic during the different hours of the day, and to each vehicle a mean time between failures (MTBT) distribution and a mean time to repair (MTTR) distribution, to compute realistic cycle times and costs on each route.

Results were discussed with Subject Matter Experts using the Face Validation technique: the project team members, potential users of the model, and subject matter experts (SMEs) review simulation output (e.g., numerical results, animations, etc.) for reasonableness. They use their estimates and intuition to compare model and system behaviors subjectively under identical input conditions and judge whether the model and its results are reasonable as in Hermann (1967). The results of the validation phase was considered acceptable by all participants of the Face Validation Workshop.

4 RESULTS AND CONCLUSIONS

The practical application of the proposed methodology led to the identification of the most suitable resources and the best allocation plan which substantially improve the cost effectiveness of the collection cycle.

The costs of the new solution compared to the current implemented, estimated a potential cost savings of approximately € 2,140 per day, which corresponds to € 451,000 over an entire year of operations.

The implementation of this re-engineering plan will, in future, benefit from the approved investments for the purchase of new class vehicles (“lateral” and “medium”) to replace the less efficient “2-axes,” “3-axes,” and “compact” currently used as shown in Figure 3.

The successful results obtained on the example application not only validate the robustness of the methodology but also demonstrate its potential for solving a wide range of transportation logistics and supply chain management problems.

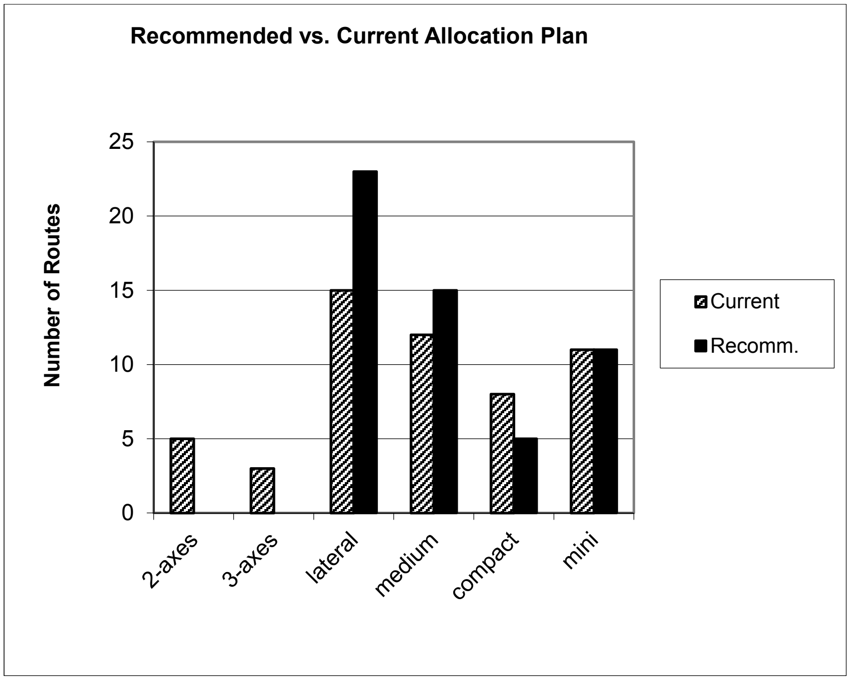

Figure 3: Number of routes assigned to each class of vehicle in the recommended (i.e., optimized) allocation plan against the current one.

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