TeMA

Journal of
Land Use, Mobility and Environment

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The cover image shows a copy of the 1987 UN report "Our Common Future – The report of the world Commission on Environment and Developments". The picture has been taken in TeMA Lab in July 2023. On the bottom, there is a collage made up of four pictures of recent climate disasters (Source: Google images)

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TeMA Journal of
Land Use, Mobility and Environment

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A platform to optimize urban deliveries with e-vans

Dealing with vehicles range and batteries recharge

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Abstract

The paper reports the results of a research targeted to develop a Decision Support System (DSS) for planning and operation of urban deliveries carried out with electric vans.

The research was included within the 2019-21 Research Program for the Electric System, coordinated by the Italian Ministry for the Ecological Transition, and has been performed by ENEA, the Italian Agency for Energy, New Technologies and Sustainable Development, and "La Sapienza" University of Rome.

The new DSS is based on meta-heuristics algorithms capable to manage a generic set of goods to be delivered by means of a generic fleet of electric vans, with the objective of minimizing the overall cost of the daily operation. The algorithm considers all the physical constraints, including vehicles batteries capacity. It is assumed that fast recharges can be performed during the delivery tours.

For the real-time operation, a monitoring system of the vehicle fleet, road network and recharge stations is assumed, based on IoT technologies, in order to detect possible unexpected events and manage them in the best way, according to the available resources time by time.

The paper describes the DSS general architecture, the optimization algorithms and the recovery procedures and shows results for two testbeds.

Keywords

Urban deliveries; Electric vans; Decision support system.

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1. Introduction

The paper describes the results of a three years research carried out within the 2019-21 Research Program for the Electric System, coordinated by the Italian Ministry for the Ecological Transition (formerly by the Italian Ministry of the Economic Development). The research has been performed jointly by ENEA, the Italian Agency for Energy, New Technologies and Sustainable Development, and "La Sapienza" University of Rome.

The research goal consists in a software tool aimed at optimizing, day by day, the delivery tours within an urban network, when transport is carried out with Battery Electric Vans (BEVs). The software is designed to manage supply and demand data of urban deliveries in order to make the logistic process more efficient, reducing both operational costs and energy and environmental impacts, but also allowing a better management of public and private facilities such as vehicles unloading areas and charging stations for electric vans. In this sense the tool is targeted not only to logistic operators but also to local public administrators.

The vehicles routing optimization for goods delivering is a topic of vast operational interest, just thinking of the thousands of deliveries that are handled every day in the context of e-commerce. Systems of optimization and management of delivery operation are already adopted by many commercial carriers involved in the deliveries of goods (Logistica Management, 2019; Iveco, 2020; Nissan, 2020; Ford, 2020; Paganoni, 2020; Zuccotti & Konstantinopoulou, 2010).

However, the use of electric vehicles is a relatively recent topic of research. When considering electric traction, the usual constraints related to vehicle routing problems, like time-windows at delivery points or vehicles load capacity, need to be taken into account jointly with the vehicles range limits linked to its battery energy capacity. This means that the daily vehicles activity program must also consider the possibility to perform suitable electric recharges during the delivery tours, using the recharge infrastructure spread in the urban area, either public or private. This leads to an increase in computational criticalities, which has been faced during the research.

Apart from this planning functionalities, the project was directed to manage, during vehicle operation, the most common unforeseen events, deriving, for instance, from anomalous traffic conditions or battery defaults, that can require real-time changes to the original schedule, rising new routes and / or recharging operations. From this perspective, the information to be acquired in real time both from the vehicles and the territory in which they operate is crucial.

In recent years, the development of the Information Technologies opened new horizons in the management of Transport and Mobility. Big amounts of data on demand behavior as well as infrastructures and vehicles status can be continuously acquired from the field much easier than in the past. At the same time, communication among users, administrators and operators can take place widely and fast, allowing both off-line analyses and on-line interventions that were unimaginable just few decades ago. In this framework, many sectoral studies and researches have focused on the design of modern decision support platforms for local administrators and stakeholders, aimed at identifying, through analytical processes, policies and actions to facilitate the transition to a more efficient planning and management. This is part of a more general attempt to reinvent cities to optimize energy consumption, and quality of life (Gargiuo et al., 2022; Staricco & Brovarone, 2016; Del Ponte, 2021; Gonzalez-Feliu & Morana, 2010; Carrese et al., 2021).

In this paper we propose an application of IoT specifically focused on urban delivery electric fleets management. A monitoring system capable to collect data from in-motion electric vehicles, unloading and recharge facilities and transfer them to a Control Center has been designed and tested. For the objectives of the research, this information must be updated at regular and short intervals, in order to allow the algorithms residing on the platform, in case of unexpected events, to rearrange the remaining vehicles tasks, taking into account new operation conditions as well as physical and commercial constraints.

The following figure illustrates the functions to support the urban distribution of goods and the expected results for the two categories of users of the platform.

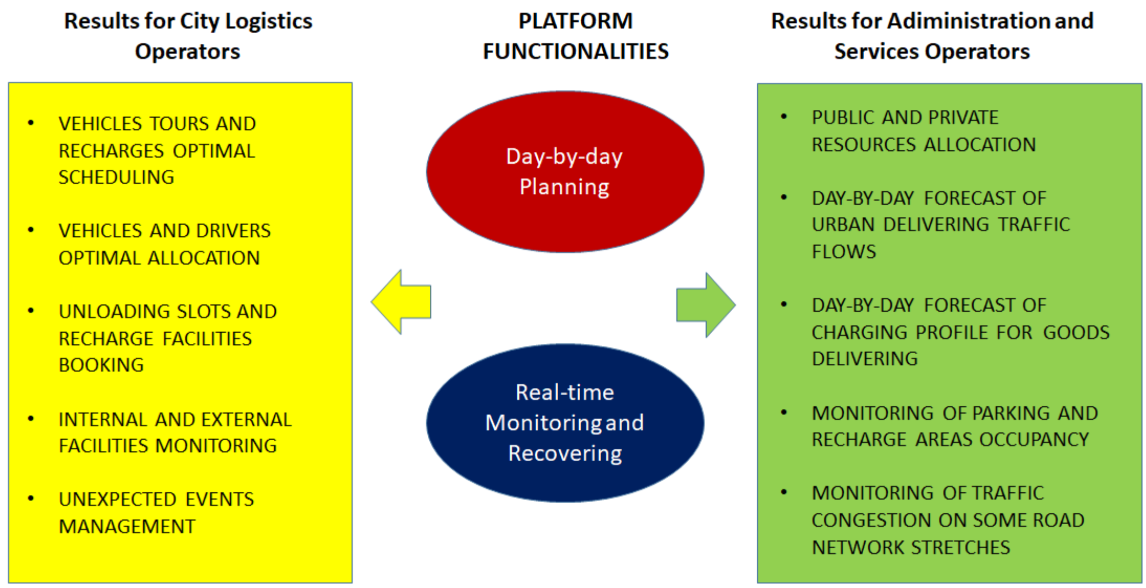

Fig.1 Functionalities of the platform for planning and operation of urban deliveries with batteries electric vans

2. State of Art of technologies

Urban areas are the hub of last mile deliveries, which to date represent the least efficient link in the entire logistics chain in terms of generating costs and negative externalities. According to recent estimates, last mile deliveries account for up to 40% of the total cost of the supply chain (Capgemini Research Institute, 2018) and are responsible for 30% of CO2 emissions and about 20% of traffic. About 80% of deliveries take place in the urban areas, 20-25% of them, in terms of travelled kms, concerns outgoing goods, 40-50% are for incoming goods, the remainder relates to goods with both origin and destination within the urban perimeter (Struttura Tecnica di Missione del MIMS, 2022). In the absence of ad hoc interventions, the number of light commercial vehicles for urban delivery of goods will increase by 36% by 2030 (WEF, 2020).

The renewal of fleets with clean or low-emission vehicles represents an indispensable opportunity towards a substantial reduction in urban negative emissions (GHG, air pollution, noise). Operators and builders consider various sustainable transport solutions, such as cargo bikes (which might contribute to the reduction of road congestion and the risk of accidents) and electric vans. The former, characterized by modest costs, are severely limited in terms of range and load capacity; electric vans on the other hand have higher costs of investment, also for the re-charging equipment.

In Italy, the light commercial vehicles market in the first semester of 2022 was of 86.700 units (ANFIA, 2022), decreasing by 11.6% compared to the same period of 2021, due to economic uncertainty. The national van market remains dominated by IC engines and, although in the past few years the sales of electric vans are increasing, in 2021 remaining limited to 2% as for purely electrics and to 7% as for the hybrid ones.

Fig.2 shows the technology split of vans in Italy in 2021, when the national LCV fleet counted about 4.34 million units, 23% of which were Euro 6. BEVs represent only 0.24% while the hybrids 0.43%.

Industrial policies are presently strongly influenced by increasingly stringent environmental regulations, as well as by energetic concerns, so that the electric gamma is rapidly enlarging. In 2022, some automakers even sell only electric van models.

Currently, battery packs guarantee an average of 100-200 km daily mileage, with an energy capacity ranging from 37 up to 70 kWh. Batteries can generally be recharged either with an AC wall-box, requiring several hours, and therefore suitable for an overnight charging, or with more powerful DC charging stations that allows for shorter charging times.

The rise of e-commerce is influencing the evolution of urban logistics so much that the use of goods transport vehicles of limited size and load capacity, such as bicycles and tricycles, drones and robots, have been introduced to carry out small deliveries within narrow areas such as urban ones. In an even more innovative scenario, the 3D printing directly at the buyer's premises can become a widespread mode of goods delivery, making it possible to virtualize freight transport on a par with what teleworking and teleservices are doing with passenger mobility.

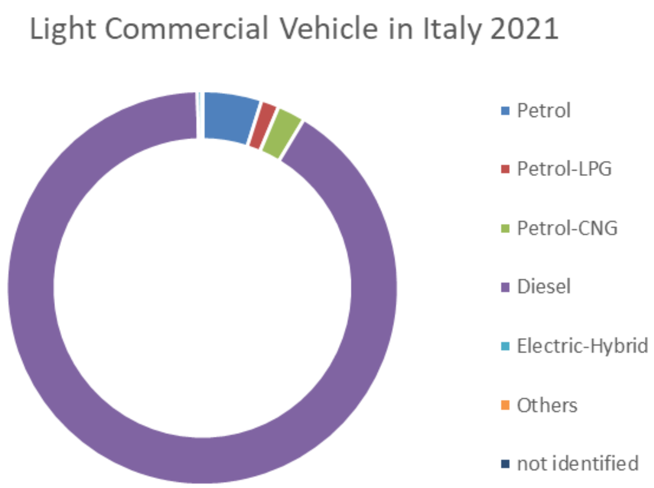

Fig.2 Light Commercial Vehicle fleet in Italy by technology, 2021 (%) – Data source ANFIA

The modern cargo bicycles, even trikes (tricycles), can be electrified and modular, this facilitates the carrying out of deliveries and, considering that e-bikes have already been successfully utilised for providing postal deliveries, it can be said that the two / three wheels are back in vogue again. Velove's Armadillo, for example, is used by numerous delivery operators, including DHL, DB Schenker, Deutsche Post, DPD, Hermes and Swiss Post. Centaur Cargo has developed a modular cargo bike for Royal PostNL and AN Post while Coolblue and Truck Trike partner with Urban Arrow and a Portland-based company is working with UPS

Cargo bicycles might also be used in other services, in addition to the distribution of small packages, such as the Cyclo Plombier, a hydraulic company that travels around Paris on cargo bikes. This allows operators to carry all of their work tools, eliminating the costs of fuel, parking, repairs and all the associated stress.

In Groningen, non-electric trikes were present long before "Mobility-As-A-Service" or "sharing economy" were coined. These very distinctive trikes have become a city institution, rent for half a day at a cost of 12 euros, still not competitive for the delivery of goods, compared to the prices charged by traditional couriers.

Numerous companies are developing drone delivery services for small loads, including Matternet (2 kg for 20 km), ZipLine (1.8 kg for 80 km), Flirtey. The DPDgroup subsidiary of the French group La Poste recently opened its second commercial line to deliver packages at medium altitude, using a drone capable of carrying 2 kg up to 15 km. The Swiss Post teamed up with Matternet to provide medical supplies, although they stopped after two incidents. Alphabet (Google's parent company) and Amazon have received clearance from the US Federal Aviation Administration to operate their drones and have started delivering via their subsidiaries, with PrimeAir (2.5kg over 25km) and Wing Aviation (2.5 kg over 25 km).

According to the European Energy Agency (EEA, 2019), in urban area bikes and e-vans can operate better than drones. In any case, all the studies recognise that the environmental benefit of using drones is limited to a small segment of the market (i.e. last mile deliveries to a single or a few recipients with a low payload).

Several players are also evaluating pilot studies for the use of autonomous electric vehicles for last mile delivery, among these: Nuro is planning to build a special vehicle that, for the first time, can keep a speed of 40 km / h. The start-up has already made several food deliveries. Two other operators are Gatik and Udelv, the former intends to specialize in the "middle mile" delivery from warehouses to stores, and has pioneered its solution with Walmart, while the latter has made test deliveries to retail stores. Amazon also aims at autonomous driving with Aurora Innovation; the company is developing a complete software package and hardware components, to allow autonomous vehicles at level 4. More recently, Amazon has also collaborated with the start-up Embark autonomous trucking company to test autonomous driving in the United States attempting to tackle the "middle mile".

In China, Alibaba is testing low-speed (15 km/h) driverless delivery robots and sidewalk delivery robots, these are smaller vehicles with the aim of allowing deliveries in areas where other types of vehicles, more traditional, are not allowed (e.g. pedestrian streets, campuses) and short deliveries in dense urban centres. This initiative is the focus for a number of start-up, including Dispatch, Marble, Robby, Starship or Kiwi Campus. These little robots are also an integral part of Amazon's multimodal delivery strategy. The company also developed its own delivery robot, a small six-wheeled electric vehicle, and tested it on a new service called Scout. Likewise, FedEx developed Roxo, a four-wheeled robot with the ability to climb a few stairs and aim for same-day delivery, and PostMates was authorised to test their vehicle on the San Francisco sidewalks.

The Ez-Pro solution proposed by Renault consists of a fleet of autonomous electric capsules, capable of transporting up to 2 tons of goods and coordinated by a leading vehicle, on which the "messenger of the future" travels, a single operator whose function it is no longer that of driving the vehicle, but of supervising the route and delivery of goods.

Both vehicle and telematics innovation can be of great importance in the re-thinking logistics systems for last mile distribution and freight transport more generally; as the connection of things (Internet of Things – IoT) grows, the possibilities of managing processes in a more informed and efficient way grow and the overview of telematic solutions aimed at last-mile services is already very wide.

Pending the marketing of autonomous vehicles, connected vehicles are already a reality: complex systems consisting of a set of Electronic Control Units (ECU) connected to each other. The technologies underlying these systems are protocols that allow different types of communication: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-everything (V2X). The "connected vehicles" therefore process a lot of information: from technical data on the condition of the vehicle or related to its use (speed, seat occupancy or maintenance status), to those on the road surface and weather conditions, or on the presence of pedestrians or other vehicles; or information relating to the location, owner or user. Some advanced features could allow the processing of biometric data, both for the authentication of the driver or user of the vehicle and for the monitoring of some of its psychophysiological parameters.

These strategies will save energy, better divide the work between the various carriers and offer a higher quality service, creating the conditions for the cost-effectiveness of last-mile delivery.

3. Theoretical hints

Researchers and practitioners have been studying the Vehicle Routing Problem (VRP) for more than 60 years (Dantzig & Ramser, 1959). It has been now declined in the problem of designing least-cost delivery routes from a depot to a set of geographically scattered customers, subject to side constraints. With the introduction of Electric Vehicles (EVs) for urban freight transport, the limited driving range represents a significant additional constraint, also due to the large time difference between refueling and recharging. Therefore, in literature, many works are addressing the Electric Vehicle Routing Problem (E-VRP), each considering different constraints and approximations.

E-VRP's goal is to design low-cost BEV (Battery Electric Vehicles) routes in order to serve a number of customers taking into account the usual constraints: vehicle load capacity, customer location and time windows, working hours, fleet size and characteristics, time-dependent travel time; moreover, vehicles range limits and re-charging possibilities must be considered, either schematically or more realistically. In a review from Erdelic & Carić (2019) 80 articles regarding E-VRP have been analyzed to determine the frequency of appearance of variants and constraints, including those specific for electric vehicles, as shown in Fig.3.

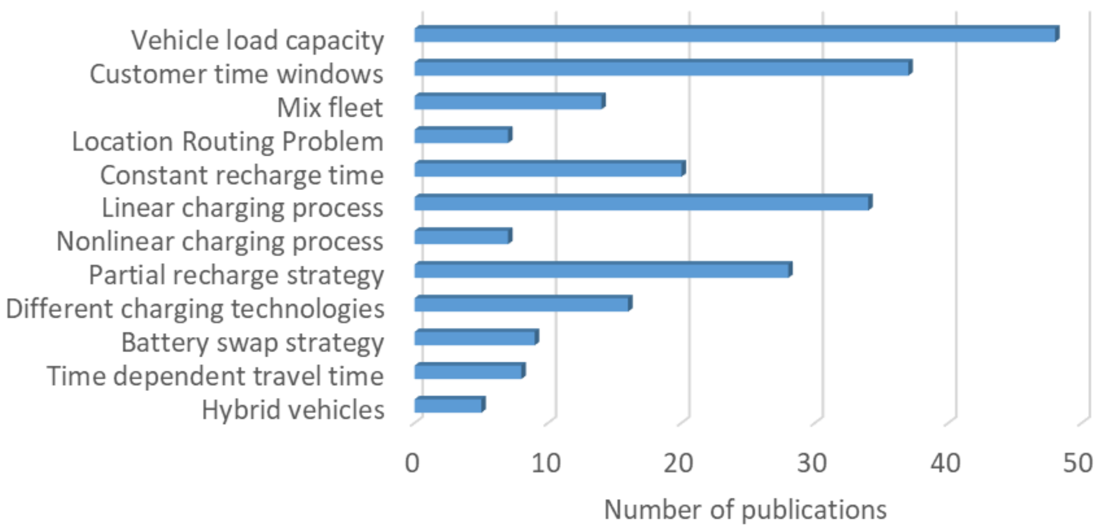

Fig.3 Frequency of Variants and Constraints in EVRP papers

The figure highlights that, as for recharging time, a linear process is considered, rather than a fixed or, on the opposite, non-linear one.

Numerous resolution procedures have been proposed to solve the VRP, and many of them, with appropriate adaptations, are also applicable to solve the problem of vehicle routing with electric vehicles (E-VRP). For small-size problems, several exact procedures have been proposed, but since this is an NP-hard problem with a large number of deliveries to be made in real scenarios, most of the procedures used in practice are heuristics, metaheuristics or hybrid combinations.

Heuristics are generally classifiable in two main families: Constructive Heuristics and Local Search Algorithms. The former iteratively inserts customers to the available routes, constructing solutions in what is commonly defined a "greedy" way, that cannot be reversed afterwards. At each step of the algorithm, an unserved customer is added to the route, along with its position in the route, according to the objective function. Two pioneering contributions are the savings method (Clarke & Wright, 1964) and the sweep algorithm (Gillett & Miller, 1974). On the other hand, Local Search algorithms, or Improvement Heuristics, start from a feasible solution and iteratively try to improve it by exploring the current solution in its neighbourhood, by applying perturbation moves. When it is not possible to find an improvement of the solution in its neighbourhood, a local optimum is reached and the search stops.

Metaheuristics, more complex frameworks of heuristics, are employed to allow the algorithm to escape from these local optima to find a better solution. Population metaheuristics are based on the definition of a population of individuals, which represent possible solutions of the VRP and go through the process of evolution. Many applications to E-VRP can be found in literature, including genetic algorithms, ant colony and particle swarm optimization. Otherwise, metaheuristics can be neighbourhood-oriented, directly addressing the problem of falling into repetition patterns, since by allowing a decrease of the objective function the risk of going back to the previous current solution must be prevented. Among this last family, the Simulated Annealing (SA) algorithm modifies the local search algorithm by introducing a randomized criterion for the selection of the new point in the current neighbourhood and for accepting the next step of the local heuristic. It is inspired by the physical cooling process of glass materials, controlling the search process through a parameter that is called temperature. The basic idea of the algorithm is to allow significant worsening of the value of the objective function in the initial stages of execution, to avoid being trapped in local optimum far from the global optimum. After a sufficient number of iterations, the algorithm is supposed to reach a part of the solution space close to the global optimum: at that point the temperature is decreased to refine the search.

For a detailed explanation of the heuristics and algorithms for vehicle routing problems the readers are referred to the works of Erdelić & Carić (2019) and Vidal et al. (2013).

4. Solution approach

As already stated, this work is aimed at developing a procedure to optimize, both in planning and operation phases, the tours for delivering goods within an urban network, when transport is carried out only with Battery Electric Vans (BEVs), by a unique carrier, from a unique sorting center.

The electric fleet can be heterogeneous, composed by vehicles of various load capacity, range and operational unit costs. Deliveries are linked to a set of delivery points, each of them characterized by a double time window within the fleet operation hours. A set of fast recharge stations is available across the delivering area, to be used if the battery State of Charge (SOC) goes under a certain lower threshold (20% of battery capacity), and a constant recharge time of 30 minutes for any considered type of vehicle.

The procedure is composed of four modules, two of which working off-line, before vehicles operation is started. A first algorithm allocates the deliveries to a subset of vehicles, optimizing the overall delivery time and cost, by matching vehicles load capacity and deliveries time-windows. A second algorithm determines the position of the vehicles on the graph and estimates energy consumption, verifying if and when the battery energy is almost down; in such a case, one (or multiple) recharge(s) is(are) inserted along the vehicle route, selecting the more suitable recharge station(s) among those available. Both these modules work without particular pressing from the time processing point of view. In fact, generally, goods to be delivered in a certain day are known at least the evening before so that more than few hours are available to search for the best solution. This is a crucial factor to set out the optimization methodology to be adopted. In our case a metaheuristic algorithm has been chosen, in the family of Simulated Annealing. The objective function minimizes the number of vehicles used, the total mileage and the total travel time, while penalizing time-window violations.

The other two codes work in real-time, during vehicles operation, in case of anomalies respect to the original schedule. The 'Recovery' code manages any default of battery State of Charge, suggesting additional or alternative recharges to those scheduled. Finally, the 'Update' code manages vehicle delays, not necessarily leading to an alert on the remaining battery range.

The flow diagram presented in Fig.4 illustrates the whole software procedure, starting from the acquisition of the characteristics of the road network, which must be schematized with an appropriately graph. The data of the specific case study are then acquired, relating to the composition and characteristics of the electric fleet as well as the attributes of the goods to be delivered, in terms of quantity, delivery points and related time constraints. In this phase, information relating to the charging infrastructure located in the area and the consumption functions of the electric vans are also collected. On the basis of these data, the two modules responsible for the off-line planning of delivery tours (Optimization and Simulation) return a sub-optimal solution. This solution is defined in terms of allocation of the goods to the vehicles, timing of the deliveries and possible recharge, as well as road routes from one delivery/recharge point to another. In addition, the vehicles positions and battery SOCs are provided at time intervals of 10 seconds.

The modules for the recovery of anomalies are launched only in a phase in which the vehicles have already begun their tours and only if, through data acquisitions from the field, there is an excessive misalignment with respect to the planned tour. This misalignment can be due to the battery's state of charge, too low than expected, or the vehicle's position, too far back. In the absence of a real monitoring system, which would have involved costly instrumentation of a real fleet and a real territory, the vehicle anomalies to test the recovery procedures are simulated randomly.

Planning and recovery codes were developed in Matlab and made available as executables compiled for the Linux operating system, while the accessory procedures for creating the work environment and the input files were developed in Python language.

The entire procedure (Fig.4) was planned and implemented in order to avoid any operator intervention once the suite has been launched. The whole procedure has been integrated in eMU, a multifunctional web-based platform developed in ENEA in order to ease the diffusion of electric mobility in urban areas.

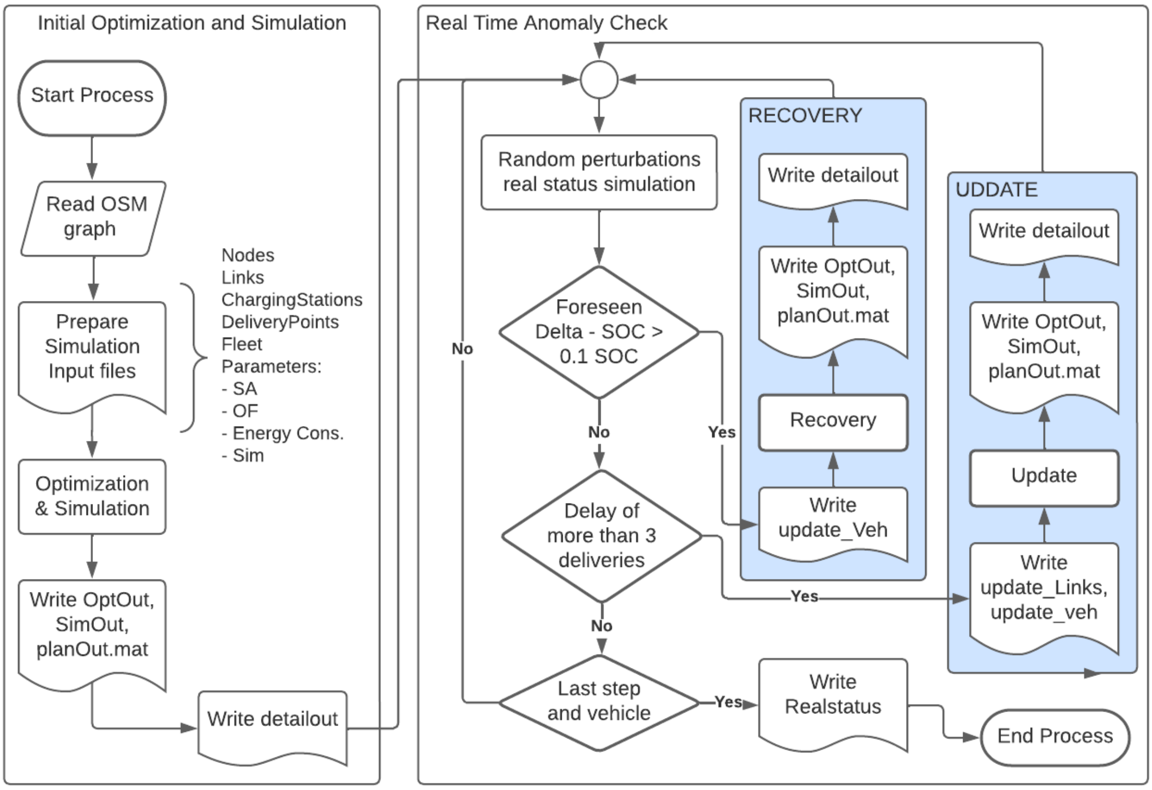

Fig.4 Optimal planning and real-time operation procedures

5. Algorithms for optimal scheduling

The vehicle routing problem (VRP) is a complex optimization problem that is typically classified as an NP-hard problem (Hashemi-Amiri et al., 2023). This means that finding the optimal solution to a VRP may require an exhaustive search of all possible solutions, which is computationally infeasible for large-scale problems. To address this challenge, various algorithms and optimization techniques have been developed to find near-optimal solutions within a reasonable amount of time.

These include heuristics, metaheuristics, and mathematical programming methods such as linear programming, mixed-integer programming, and dynamic programming (Rahmanifar etal., 2023). In this work, the proposed routing problem is solved with the use of a Simulated Annealing algorithm , which searches for the most efficient lap itinerary. SA is utilized by many scholars to solve different optimization problems and specifically, this algorithm is among one the most preferred used algorithms to address VRP (Colombaroni et al., 2020). The algorithm works according to the cooling physics process which is also called the annealing process. This is the procedure of low energy-state crystallization of molecular metal arrangements by slowing down of the temperature after being subjected to high heat (Kirkpatrick & Swendsen, 1985). The optimization process takes place as follows:

- an initial solution (S1) is created (see below);
- the solution is perturbed;
- the cost of the new solution is evaluated;
- a probabilistic function compares the cost of the new and previous solutions and decides which one to keep;

- the procedure of perturbation, evaluation and comparison is iterated for L times;
- the parameter of the probabilistic function (temperature) is decreased and the best solution of the L iterations is chosen to restart in the next cycle;

This process continues until the temperature drops below a final temperature value, and the found solution is the result of the optimization. This process is explained in Fig.5.

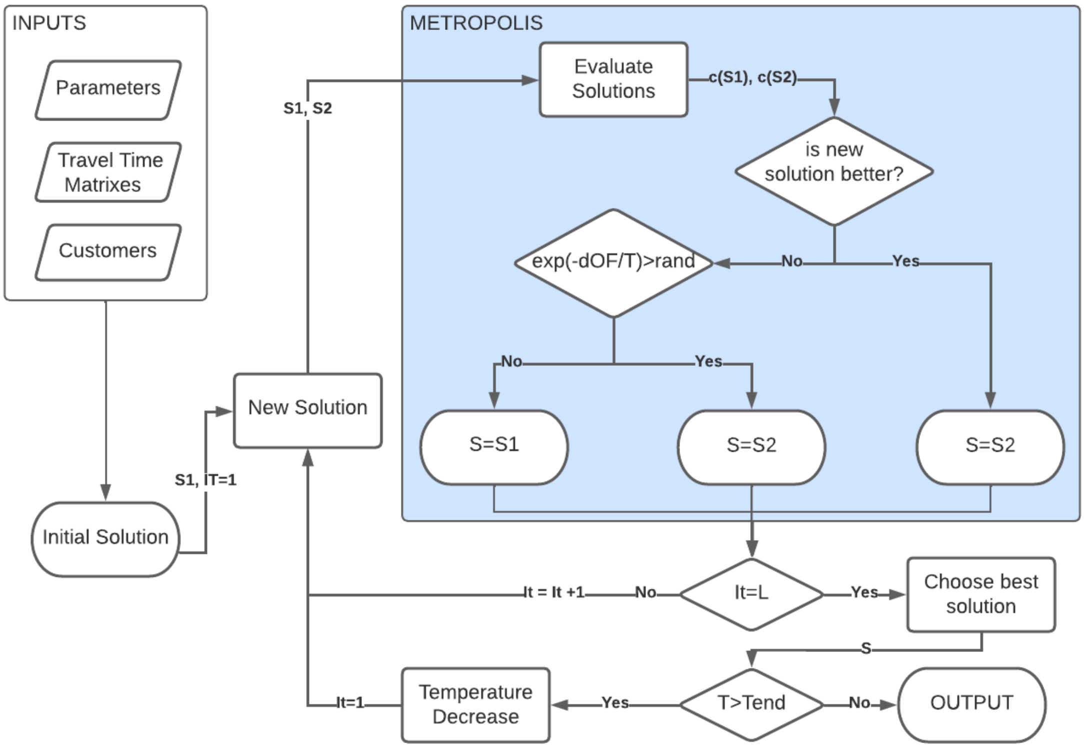

Fig.5 Optimization procedure with Simulated Annealing algorithm

The initial solution (S1) is created starting at the depot, and selecting the closest delivery point. The second delivery is determined by searching for the delivery point closest to the first one, and iteratively for the following deliveries. Time windows are not considered since they are used as a soft constraint. Once the distance of the tour overcomes the driving range of the vehicle, the itinerary of that vehicle is terminated adding a stop at the depot. The procedure of assigning deliveries to vehicles starts again with the remaining deliveries using the following available vehicle.

The perturbation of the solution can follow three different strategies: Swap, where two deliveries are randomly selected and their order is switched, Reversion, where a random set of successive deliveries is selected and their order is reversed, or Insertion, where two deliveries are selected and the first one is moved right after the second one.

The new solution is then evaluated determining its associated cost and it is verified that no autonomy or load constraints are exceeded. The cost is calculated through a linear combination of travelled distance, travel time and number of vehicles, in addition to the time windows violation penalties. The weights used to define the objective function are:

- operating cost of the vehicle per km travelled (oc);
- hourly operating cost (including driver cost - tc);
- additional cost for each vehicle used (use and depreciation - vc);
- additional cost for every time window violation (wc).

The Objective Function is therefore defined as:

$$OF = oc * dist + tc * time + vc * n\_veh + wc * tw\_violation \tag{1}$$

Where dist is the distance run in km, time is the time required to run the distance in seconds, n_veh is the number of vehicles used for the deliveries and tw_violation is the total time of the time window violations.
The "Metropolis" function then compares the current solution (S1) with the new one (S2) according to the values of the objective function and the current value of the temperature parameter. The choice is not deterministic, but is subject to a probabilistic assessment: the new solution can be accepted even though the cost is higher than the previous solution. If the analyzed itinerary is the best choice, the new solution is automatically accepted, but if the value of the objective function is lower than that of the previous solution, the solution can still be approved with a probability expressed as a function of the difference between the two values. The new solution is accepted if:

$$e^{(-\frac{\Delta OF}{T})} > p \tag{2}$$

Where *ΔOF* is the difference between the objective function of the two solutions, T is the temperature, and p is a real number extracted from a uniform distribution in the interval [0,1].

6. Monitoring and recovery procedure: the Recovery and Update processes

When considering electric vehicles, additional issues related to vehicle battery and charging stations defaults may occur in addition to the ordinary problematics related to traffic or mishaps at delivery destinations. This causes an increase of possible critical events, in particular associated to the need to suddenly include a charging event within the planned trip. Our system is designed to face such operational issues in real time. This is performed by two distinct procedures that are activated depending on the kind of problem the vehicle is dealing with. The Recovery procedure is activated in case of an unexpected discharge of the vehicle battery, while the Update process handles any delay of the vehicle, recomputing the optimal path and adding or rescheduling new recharging stops if required.
The recovery function allows to consider the need of sending a vehicle to a charging station, which was not initially foreseen in the plan, in case the power reserve is not sufficient to complete the round of deliveries due to unpredicted events that have reduced the charge compared to planning. The module calculates the current position of the vehicle and, from that position, selects the closest charging station. The schedule is then updated according to the new itinerary.
The update function offers the possibility to re-optimize the order of the remaining deliveries of a vehicle if during the monitoring operations a significant deviation of the travel times or the position of the vehicle with respect to the planning is received from the platform. The characteristics of the road network and the performance of the routes can undergo changes during daily operations. As a result, the travel time of electric vehicles may vary and it is reasonable to re-optimize the remaining part of the journey in case of significant changes in travel times. Also, the current position of the vehicle itself may be different from the plan and in this case a re-optimization for the rest of the lap may be required.
Both Recovery and Update modules act during the operational phase of the whole process. Once the Optimization module has identified a good vehicle routing, including the required stops at charging stations, all involved vehicles start their trip following the planned routes, being continuously monitored in real time.
In fact, the real vehicles operation is always affected by a misalignment respect to the planned one, due to unavoidable approximation of theoretical values (trip time, energy consumption, battery capacity) and unexpected events (traffic conditions, time waste, technical defaults, …). Thus, a proper recovery procedure must be capable to tolerate a certain amount of error, up to not overtake physical or operational constraints, such as vehicles battery capacity or deliveries time windows. In our system Recovery and Update procedure

are launched when either real battery State of Charge or real vehicle position differ from the planned ones more than pre-specified threshold values.

The following Fig.6 shows a schematic example of route rearrangement when a "battery alarm" is acquired by the monitoring system from a vehicle during its delivering operation: the nearest available recharging point is immediately identified and a new recharge is inserted in the tour before next deliveries. Possible recharges previously planned are automatically deleted and other recharges are planned to permit the end of the tour, if necessary. No changes in the deliveries sequence are provided but only recharge rescheduling.

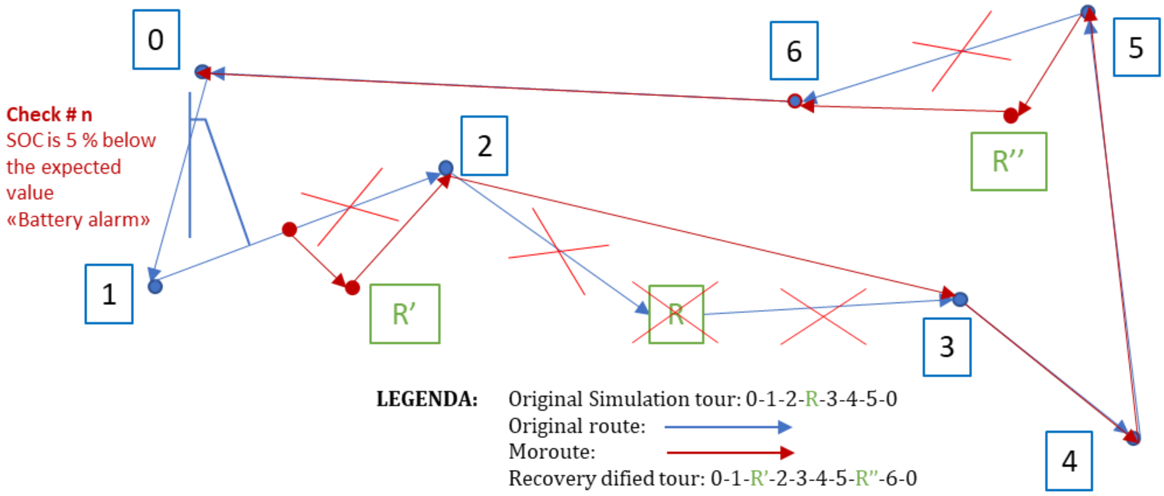

Fig.6 Recovery rationale

Vice versa, when a delay is registered respect to the schedule, a total rearrangement of the remaining deliveries is carried out, taking into account both destinations time-windows and remaining vehicle range, as well as available recharge opportunities, as schematically shown in the subsequent Fig.7.

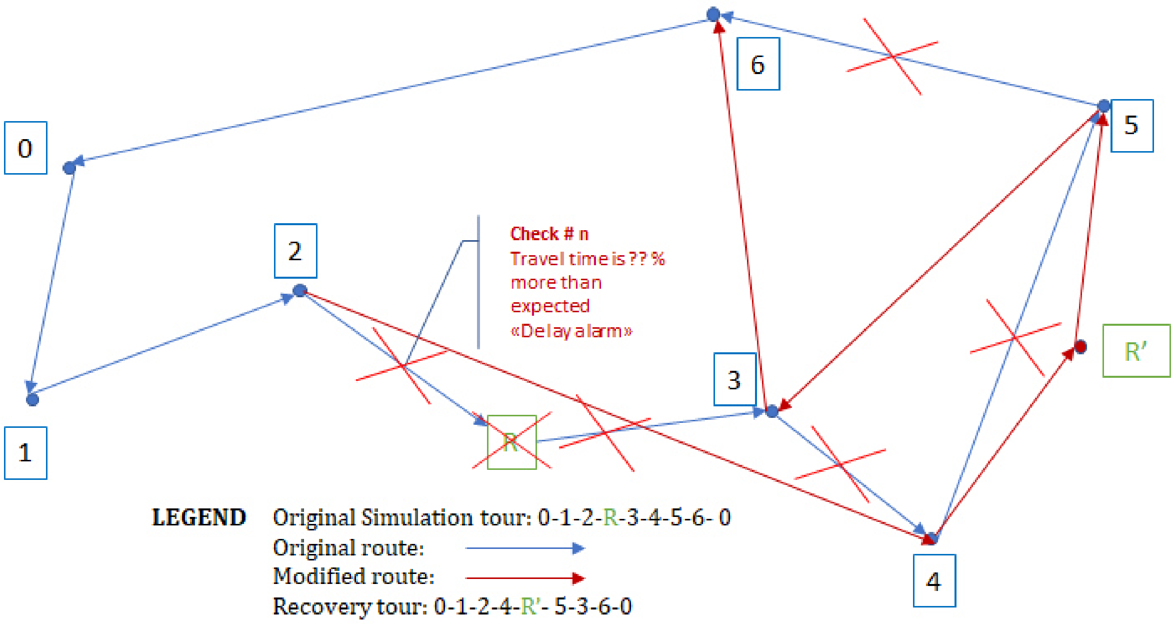

Fig.7 Update rationale

The check frequency has been set to 10 seconds. This requires to simulate the battery charge and vehicle position along the planned tour with a very high time resolution, at least less than 10 seconds, in order to determine expected values when a check respect to real conditions is carried out.

Periodically the distance between the real status and the planned status of the vehicle is computed for a set of parameters and compared with predetermined thresholds. If the distance between one of the considered parameters becomes larger than the corresponding threshold, the system automatically generates the files containing the required information to start a recovery or update for the vehicle. These processes can be repeated several times during the day in order to correct the path and the delivery process as many times as required by the forcing of the external conditions. Moreover, the recovery or update processes are run only for one vehicle per time, in order to allow to modify only the required paths and deliveries, without disturbing the other vehicles, on schedule at the time of launching, and therefore optimizing the time of recovery and update for each vehicle.

The system is built to acquire information from sensors onboard of vehicles. Yet, in our study the real status of the vehicles is simulated by adding a set of random perturbations to the planned delivery trips: every 10 seconds a delay of 10 seconds and an 0.01 kWh increase in battery discharge is randomly added with 20% probability to the actual status of the vehicle. Contrary to the real case, when both increments and decrements in the delay are possible, in this configuration only a monotonic increase is allowed, in order to test the system under an over-realistic stress.

Separate checks are carried on for discharge and delay in deliveries, in order to activate separate recovery processes. Battery status is checked every 5 minutes. Both absolute SOC value and deviation from expected discharge are monitored, in order to avoid unnecessary recharges when a vehicle is about to conclude its delivery trip. The chosen thresholds, that can be changed by the operator, imply to send a vehicle to a recharging station if its SOC is lower than 20% of its total capacity and if at the same time its value is 5% lower respect to the foreseen one. This is handled by the Recovery process, described above. In particular the Recovery resets all future planned recharging stops and plans an immediate new recharge as well as any other further recharge required up to the end of the delivery trip.

The second check is related to the Update process, and in particular to the delay of the vehicle respect to the expected position and performed deliveries. If the difference between the expected and performed deliveries at the time of check is larger than 3 (operator chosen parameter), the Update process is launched. As described in the case of the Recovery process, also in the Update process the planned path is reset and is recomputed in order to optimize the remaining deliveries by considering the updated status of traffic, using real time velocities associated to the arcs of the graph. Moreover, if required, new stops for recharging are planned up to the end of the delivery tour.

7. The monitoring system

In order to allow for the comparison between planned and real status of critical variables, a monitoring system from the field has been designed and partially tested, as described hereby.

7.1 Getting vehicle data

An embedded system has been developed, which is able to interface with the CAN BUS of the vehicle and transmit the collected data to a remote controller for subsequent processing.

The information of interest of the vehicle concerns the instantaneous position and speed and the state of charge (SoC) of the battery. The issue of capturing data from a moving vehicle in real time has been addressed in the past to pursue a variety of goals. Often, for example, the primary objective has been to study vehicle emissions and fuel consumption. Over time, different technologies aimed at capturing real-time data from the vehicle have been developed.

In any case, to achieve this goal it is necessary that an "Onboard Unit" (OBD), a tool aimed at data acquisition, is installed on the vehicle. It is therefore necessary to identify a so-called embedded system, able to connect to the standard OBD port of the vehicle, to acquire the data of interest, process them and transmit them to a monitoring and remote control platform (Fig.8).

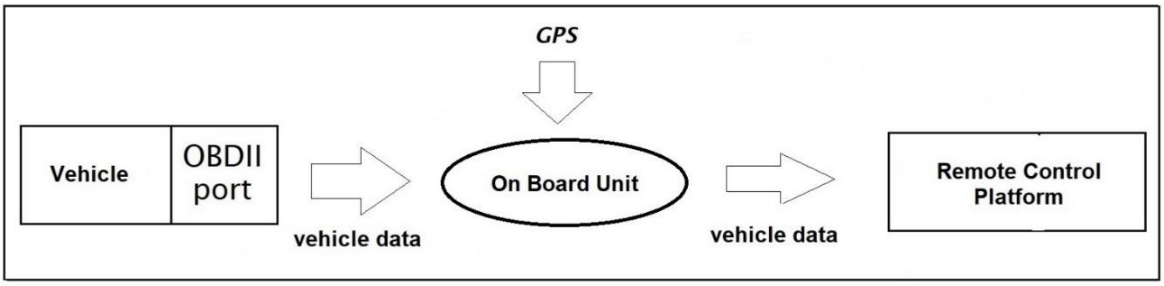

Fig.8 On-board unit information exchange

The system embedded on board the vehicle is complex, composed of several units, each with specific and well-defined tasks (Fig.9). To connect to the standard OBD port, capture the information and interpret it correctly, we used a CAN USB interface device.

It is able to read the messages exchanged on the CAN BUS of the vehicle and interpret them thanks to the use of special APIs usually written in a widespread programming language, such as C or Python. For this purpose, it is equipped with a DB9 serial port to connect to the vehicle's OBD port, and a USB output port to connect to the control device. The control device we used is a Raspberry PI 4 with a Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz processor, and 8GB LPDDR4-3200 SDRAM. The Raspberry PI device is equipped with the native Raspbian operating system based on the Debian Linux distribution. The acquisition software developed by ENEA Researchers and based on the API provided by the CAN USB device has been installed over the Raspbian operating system.

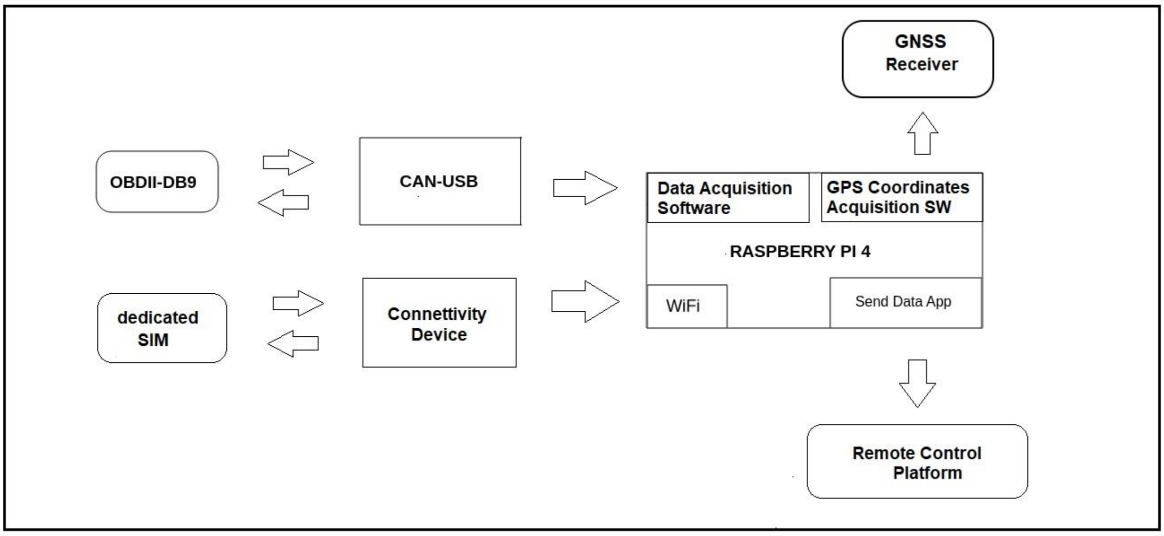

Fig.9 On-board unit architecture

These three processes are activated at regular intervals in time, to be synchronized with each other. The main process that manages the timing and synchronization of all other processes is the Scheduler process, based on the Linux crontab daemon on the Raspberry PI.

The scheduler, at fixed time intervals, activates the three other processes, with a delay from each other, so that the results of the processing can be collected and packaged in the form useful for transmission, and sent to the remote controller for further processing.

In the following Tab.1 the most relevant data that can be acquired from the vehicle are shown.

Field	Unit/format	Description
Data	YYYYMMDD	Date
Ora	hhmmss	Time
SoC	%	Battery State of Charge
motorRPM	rpm	Motor Angular rate
battA	A	Battery Charge Electric Current
battV	V	Battery Charge Voltage
AvBattery	W	Available Battery Power
Vvehicle	m/s	Vehicle Speed
qcComm	A	Quick Charge Electric Current
qcVoltage	V	Quick Charge Voltage
chargeRem	minute	Time to get battery fully charged

Tab.1 Data acquired from vehicles

7.2 Getting surrounding information

Since electric vehicles often have a limited range, to real-time optimize travels in the urban area, it is necessary to acquire the location of charging stations, in order to identify the unoccupied and available ones, closest to the vehicle when the battery needs to be recharged.

This information must be sent to the remote-control platform and must also be updated at regular intervals, in order to have a constant full knowledge of the (mapped) location of available charging stations, to be used when needed.

To acquire the free/busy status from the charging station, local magnetic field sensors are installed on the ground. The sensor measures the change in the Earth's natural (ambient) magnetic field caused by the presence of vehicles or other ferromagnetic objects close to it.

The information about the free/busy status of the charging station is sent by the sensor to a Local Gateway, which is able to communicate with the Remote Control Platform (Fig.10). At regular intervals during the day, the Remote Controller interrogates the Local Gateway to get information about all monitored charging seats, as listed above:

- position, expressed in terms of latitude and longitude coordinates;
- date and time of the detection;
- binary information about the occupation or not of the parking space.

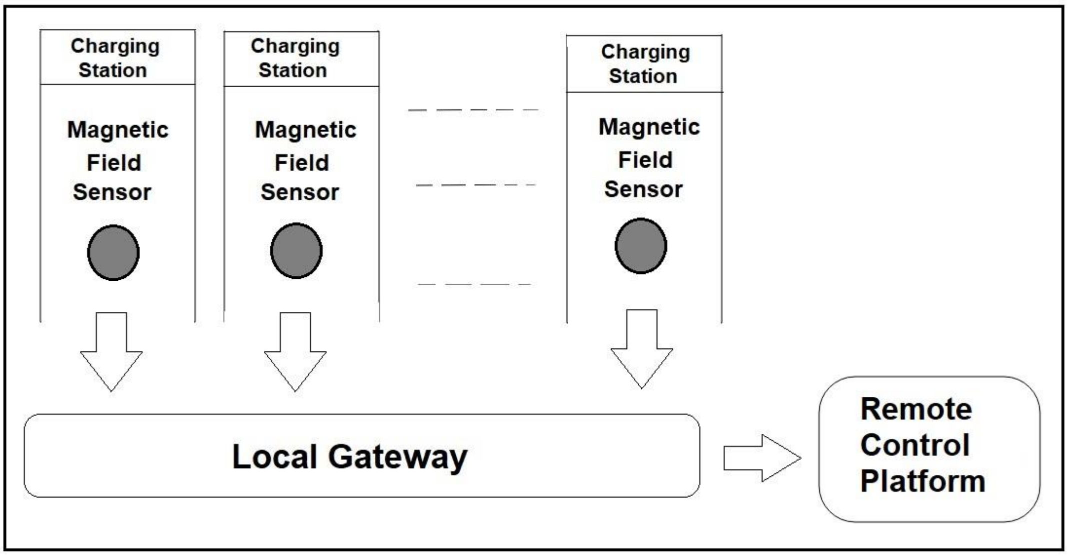

Fig.10 Architecture for acquisition of information from recharge and unloading stalls

8. The test case

Performance and effectiveness of the proposed system have been verified by implementing two real size testbeds containing 209 delivery points through the city of Rome, as shown in the Fig.11.

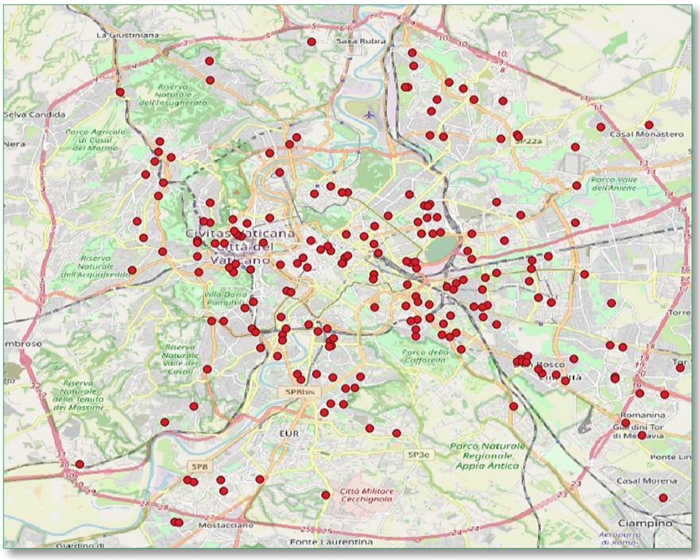

Fig.11 Testbeds' delivery points map

The differences between testbeds are related to the demand for each delivery point and the time-windows scattering, so that the second case results more challenging than the first one, as schematically reported in Tab.2.

Test #	N° of Delivery Points	Time Windows ranges [minutes from 00:00]	Total Demand [kg]	Total fleet capacity [kg]	Numbers of vehicles
1	209	(480-780), (520-780)	12,370	18,400	10
2	209	(480-780), (520-780) (500-650), (550-750)	18,362	18,400	10

Tab.2 Main testbeds' characteristics

The available vehicle fleet is the same for the two testbeds: two mini vans (450 kg capacity), two medium vans (1,100 kg capacity) and six small trucks (2,550 kg capacity).

A set of KPI has then been chosen in order to evaluate the quality of optimization performed in the two cases. Results are shown in Tab.3.

Performance Indicator	#1	#2
Total distance Traveled by all vehicles	610.3 km	1,137.4 km
Total time traveled by all vehicles	717.6 min	1,288 min
Objective function value	1,789.3	2,701.1
Capacity violation	0	0
Earliness	0	0
Tardiness	0	0
Travel constraint violation	0	0
Unit energy consumption	31.6 Wh/kg	29.7 Wh/kg
Number of used vehicles	7	10
Number of recharging by all vehicles	4	5
Running Time	274.3 seconds	271.4 seconds

Tab.3 Overall performance indicators of planning results

Results show that an increasing number of vehicles is needed as the demand gets larger, with consequent larger total travel times and distances.

Algorithm running times are similar since they mainly depend on the optimization parameters and not on demand characteristics such as time windows or total demand. For test #1, where seven vehicles are used for deliveries, four of which with scheduled recharges during their trips, vehicles performance indicators are reported in Tab.4.

#vehicle	DISTANCE TRAVELED TO LAST DELIVERY (KM)	TIME TRAVELED (MIN)	CAPACITY (KG)	UTILIZED CAPACITY (KG)	NUMBER OF DELIVERIES	CONSUMED ENERGY (KWH)	NUMBER OF RECHARGING
1654	64.93382	647.4999	1,100	826	13	18.78975	0
5381	101.9029	817.1348	2,550	2,264	38	64.38861	1
2843	89.43698	748.6876	2,550	1,777	29	53.44788	1
8464	76.37869	775.3624	2,550	1,772	30	43.4429	1
6184	125.9067	774.0042	2,550	1,500	29	71.56418	1
6185	66.24281	745.3154	2,550	2,162	37	42.2879	0
6188	72.68141	755.093	2,550	2,069	33	46.00743	0

Tab.4 Detail performance indicators of #1 testbed' planning results

A recovery procedure has been launched, when the real battery SOC of vehicle #2843 detected by the monitoring system was lower than expected, not allowing to perform all the remaining deliveries before the scheduled recharge.

With the information on the current position of the vehicle, the last delivery point and the battery state of charge, the Recovery function found the nearest recharging station and, after adding this charging point to the trip, updated the tour for the remaining deliveries.

The strings in Tab.4 represent the sequence of delivery and recharge points of the tour based on the result of the planning (P) and after the application of a Recovery (R). The points indicated with code zero (highlighted in red) within the tour represent the charging station. Delivery points in green represent the last delivery before applying the recovery procedure. The original recharge provided by the end of the planned tour is replaced with an earlier one and a second recharge is inserted at the very end of the updated tour, after all deliveries are carried out.

P	28	99	41	51	61	61	28	81	-	94	71	34	66	93	49	51	55	100	72	24	30	66	51	91	57	77	0	25	48	90	83	-
R	28	99	41	51	61	61	28	81	0	94	71	34	66	93	49	51	55	100	72	24	30	66	51	91	57	77	-	25	48	90	83	0

Tab.5 Vehicle #2483 Original (P) and updated (R) sequence of delivery and recharge points

The following figures show the rendering of original and updated tours by the User Graphic Interface of the ENEA platform that integrates the Optimal Deliveries modules described in this paper. Original tours are plotted with a semi-transparent line while the updated ones are marked with bold lines. Large part of the new paths is often over imposed to the old ones.

In Fig.12 an example of a Recovery result is shown on map. The process is activated just after the delivery at point 11 has been carried out, so that the vehicle is diverted toward the closest recharging station. The vehicle is then sent back on the original path in order to restart the delivery sequence from delivery number 12.

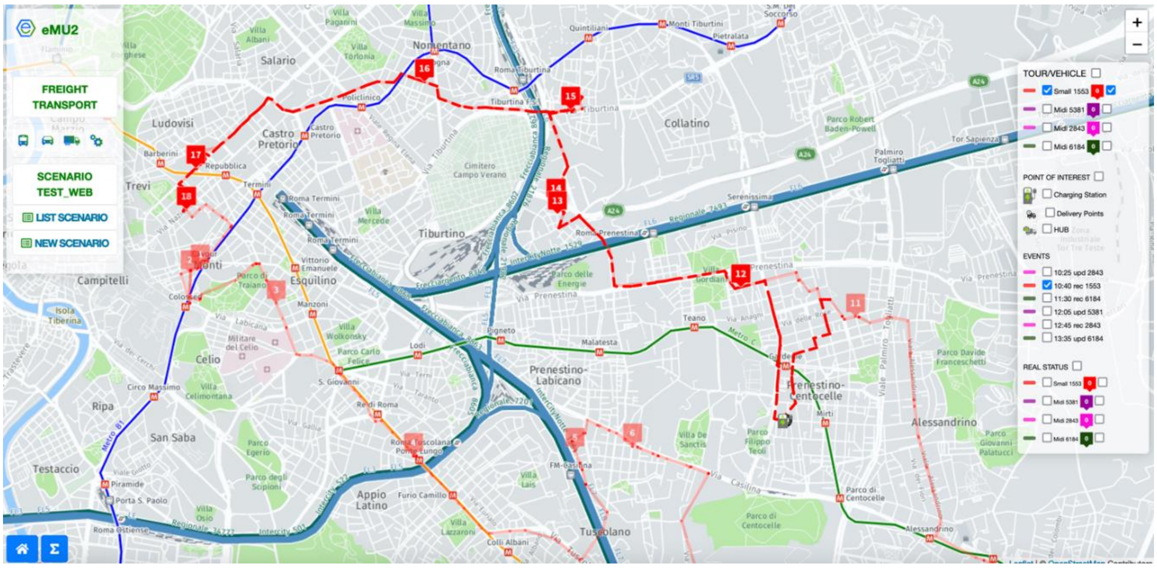

Fig.12 Graphical rendering of a Recovery' results, when a default in battery SOC is detected

In Fig.13 an example of Update is shown for another vehicle. The Update starts from the delivery number 18, due to an excess of delay respect to scheduled time; the path is deeply modified due to the updated speeds associated to the arcs of the graph.

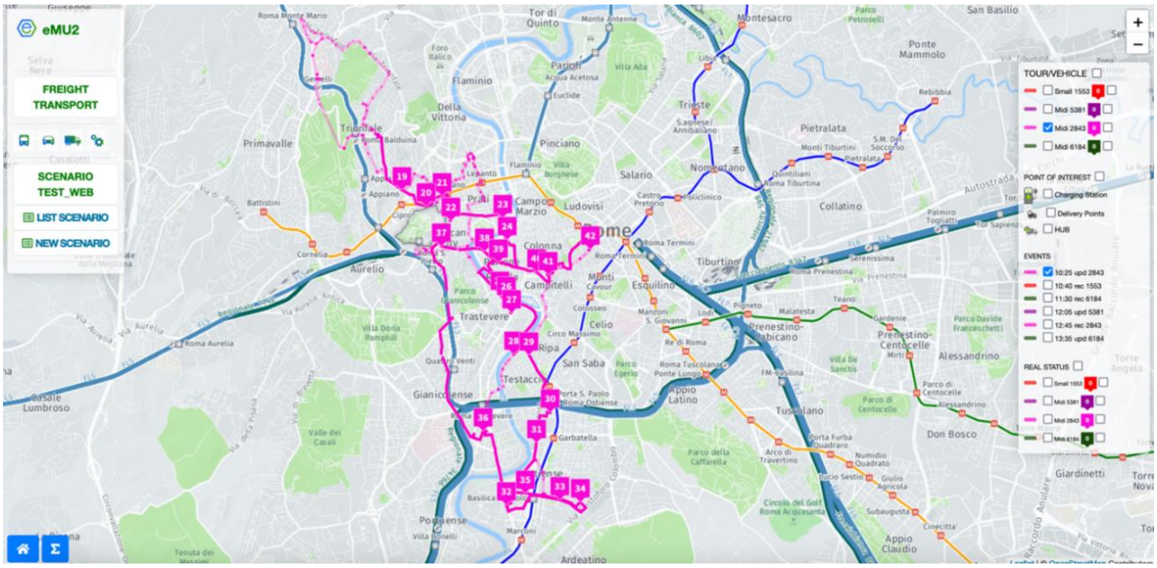

Fig.13 Graphical rendering of an Update' results, when a default in battery SOC is detected

9. Remarks

This paper proposes a general methodology to optimize BEVs operation in city logistics, taking into account possible recharge needs. Energy refuels are considered since the off-line delivery planning, adding a new complexity to the classic VRP with Time-Windows. Moreover the research proposes the possibility of activating a recovery process if unexpected events, such as battery defaults or delays due to traffic congestion or other inconveniences occur, to be monitored on-field. The performance of the proposed tool has been investigated by implementing two real-size tests consisting of a large number of delivery points and vehicles. Through the tests, different performance indicators of the initial optimization procedure have been calculated, showing a good level of results, as well as of the real-time rearrangement, both in case of additional recharge needs and delays, corresponding to the expected results.

The system is aimed at building an integrated facility to plan and handle deliveries using electric vehicles, including online monitoring of each vehicle status and of the available charging stations. All available information is handled by a central monitoring station, capable to prepare the initial planning, receive information from the field, and react to unexpected events, in order to rearrange the delivery plan to correctly fulfill the complete delivery plan.

More work needs to be performed in order to integrate the system with real acquisition of the traffic status, needed for a better evaluation of the update processes. Though, the described platform can be a good candidate for both delivery operators and city administrations. The formers to better plan and handle delivery schedules with the additional constraints related to electric vehicles and their limited autonomy, the latter in order to better handle three crucial urban mobility factors: a) freight vehicles flows integration into ordinary traffic; b) early detection of traffic anomalies through floating fleets which can operate as additional traffic sensors , c) freight vehicles parking slot and recharging infrastructure design and their real time optimal handling, Administrators functionalities require to operate the proposed platform at an upper centralized level, collecting data from single last-mile operators and, possibly, if commercial agreements are dealt, to set up public-private infrastructures such as Urban Distribution Centers allowing an even more coordinated last-mile handling.

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Fig.1: ENEA, Italian Agency for New technologies, Energy and sustainable development, 2022;

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Fig.6: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022;

Fig.7: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022;

Fig.8: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022;

Fig.9: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022;

Fig.10: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022;

Fig.11: Sapienza University of Rome;

Fig.12: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022;

Fig.13: ENEA Italian Agency for New technologies, Energy and sustainable development, 2022.

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