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DESIGNING EV CHARGING STATIONS DEPLOYMENT THROUGH HOLISTIC SIMULATIONS: THE SANEVEC PROJECT

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Abstract

To determine the optimal location of the large number of urban public charging stations that will have to be deployed in the following years to transition to electric vehicles (EVs) is a challenging task, as it is intimately interconnected with the complexity of urban traffic and electric grid operation. The city is a complex system in which emerging patterns such as traffic jams, and instabilities or even outages in the electric grid are difficult to predict. The layout of charging stations can alter those patterns in traffic and electric grid operation, with consequences to mobility, air quality, and electric system. The present article presents the concept under the research project SANEVEC. It will build a framework for the optimal determination of the location of EV charging stations in a city based on simulation, which will be able to reproduce the feedback effects between all the variables involved: locations of the stations, traffic patterns, characteristics, and operation of the electricity grid, charging fees and air quality in the city. It will employ artificial intelligence methods to find high-quality station location solutions from the simulations and to predict the air quality in the city.

1 Introduction

The global climate crisis, caused mainly by greenhouse gas emissions, is a critical problem facing humanity. One of the main contributors to these emissions is the transport sector, which accounts for a substantial share of total CO_2 equivalents. Road transport constitutes a significant portion of overall mobility. The sector, therefore, needs to transition to electric vehicles (EVs), and that will require an extensive public charging infrastructure. Forecasts for 2030 indicate the need for hundreds of thousands of public charging points, a sharp increase over the number available a decade earlier. In Europe as a whole, electric mobility is expected to account for around 55% of all mobility in 2030, considering all types of vehicles, in the existing policies scenario, according to a study carried out by the International Energy Agency [1].

Additionally, urban traffic is a typical case of a complex system consisting of many interacting components that give rise to emergent properties at the global level, which are difficult to predict in advance except by simulation. One emergent property of urban traffic is the occurrence of traffic jams, and the location of charging stations (CSs) is capable of altering the patterns of traffic jams formed in a city, as we have recently demonstrated [2]. Such traffic patterns determine air pollution levels because vehicles using fossil fuels are involved in them. As a result, the air quality in the city, and its carbon footprint are influenced by the above factors. On the other hand, the location of CSs is also influenced by the characteristics of the

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electric grid of the city. Furthermore, their activity has an influence on the operation of the electric grid, and can give rise to instabilities or even outages on it.

Therefore, finding the optimal location of urban charging stations is a complex problem determined by the mutual interrelationship between different variables: locations of the stations, traffic patterns, characteristics and operation of the electricity grid, charging fees, and air quality in the city.

Until now, the vast majority of methods for determining the optimal location of charging stations in a city have been based on the analysis of previously collected data, such as traffic patterns or grid usage. But due to the feedback and synergies between all the variables listed above, this method is inadequate because dynamic changes in one of the variables can modify the other ones. In particular, the projected location of new stations can change traffic patterns and alter the output of all indicated variables.

In this paper, we present the concept under the research project SANEVEC (“A simulation approach to determine the deployment of an urban network of electric vehicle charging stations for environmental and social benefits"), which has been funded by the Ministry of Science and Innovation of Spain and by the European Union under the NextGenerationEU program. SANEVEC will tackle the problem outlined above by employing microscopic simulations that take into account all the aforementioned factors and can predict the effects of their interrelations, coupled with artificial intelligence techniques.

2 State of the Art

Due to the relevance of the topic, it has received extensive research attention in recent years from many different perspectives. However, the vast majority of the works do not take into account the effects of charging station placement on traffic. Furthermore, a large part of them are based on the analysis of aggregated data of fossil-fuelled vehicle trajectories, and therefore they do not take into account changes in activity patterns due to electric vehicles.

We propose to address the problem through direct simulation using microscopic models, which represent vehicles as individual entities and simulate their behaviour using rules that take into account the behaviour of other vehicles in their immediate vicinity.

Two types of microscopic models have been used to model traffic: cellular automata (CA) and agent-based models (ABM).

CA are a class of mathematical systems with spatial and temporal discrete character, local interaction and synchronous parallel dynamical evolution [3]. They have been successfully used to model vehicular traffic since the works by K. Nagel and M. Schreckenberg [4], B. Chopard et al. [5] , and later by X.G. Li [6], and Y. Zheng [7], among others. In relation to electric vehicles, Xiang et al. [8] have employed a CA model to study the electricity demand of a charging station for different traffic flows, but with a model of very limited extent, which only includes one road, one intersection, and one charging station. Therefore, they did not investigate the effect of the electric network of charging stations on traffic flows.

ABMs simulate the actions and interactions of a set of autonomous elements called agents. Prominent examples of their use as a traffic model are the works of Chen [9] and Waraich [10]. The study by Viswanathan [11] used an ABM model to investigate the optimal allocation of charging stations, although in that model vehicles had fixed routes (based on daily traffic data) from an origin to a destination, so it lacks realism.

Finally, the work of Zhai et al. [12] is perhaps the most similar to the approach of this project. They used a hybrid CA-ABM model, but did not use a microscopic model, instead defining each cell as a 1 km long road section, which can accommodate many vehicles. Due to the coarse granularity of this model, its accuracy is not sufficient to simulate the dynamic traffic processes that can take place in a real city and to capture emergent properties of traffic as a complex system, such as traffic jams, and their effects on traffic density and charging demand.

To the best of our knowledge, no other development of a model and a simulation framework with such a holistic approach as the one that will be implemented in the SANEVEC project has been carried out.

3 The Underlying Concept of SANEVEC

In the SANEVEC project, a framework will be developed for the optimal determination of the location of EV charging stations in a city, which will be based on simulation. It will be able to reproduce the feedback effects between all the variables involved: locations of the stations, traffic patterns, characteristics and operation of the electricity grid, charging fees and air quality in the city. It will also integrate artificial intelligence methods to find high quality station location solutions from the simulations and to predict the air quality in the city. The aim will be to obtain environmental and social benefits, associated with reducing environmental pollution and carbon footprint in the city and improving the smooth flow of urban traffic and electric vehicle charging operations.

The project will employ a combination of computational technologies: simulation techniques to form the basis of a digital tool with a holistic approach to plan the operation of the complex urban system and forecast its evolution and consequences, using agent-based models and cellular automata; artificial intelligence to optimise the location of charging stations (genetic algorithm) and to make multi-day forecasts of air quality in the city (deep learning); high-performance computing techniques to ensure that the framework has adequate performance and scalability to be useful to simulate a complete city.

3.1 Starting hypothesis

The starting hypothesis of the project are:

1. Analysis of previous data, such as traffic patterns or electric grid usage, is not the best methodology to design the deployment of the network of electric vehicle charging stations, because their ubication and characteristics affect urban traffic and electric grid usage and can modify them.

2. Simulation using a microscopic model is a better methodology than previous data analysis to design the deployment of the network of electric vehicle charging stations, because it can take into account its effect on urban traffic and electric grid usage.
3. Urban traffic patterns (for example traffic jams), which are influenced and modified by the network of EV charging stations, have a direct influence in air-quality measures and carbon footprint of the city.

A previous work has already been carried out to verify the fulfillment of the key elements of the initial hypotheses. To this end, a model based on agents and cellular automata of the traffic dynamics with electric and fossil fuel vehicles, as well as of the recharging processes, has been developed. It has been implemented by developing a simulator, called SIMTRAVEL [13], which allowed us to validate the concept ideas through simulations on a synthetic city.

Let us describe the simulation model and the concept under SIMTRAVEL (further explained in [2]), which form the basis from which the SANEVEC project will be built.

SIMTRAVEL and the traffic simulator to be developed in the SANEVEC project are based on a cellular-automata and agent-based microscopic hybrid model. Its structure of the simulation model is described graphically in Fig. 1 The model of the city is based on a cellular automaton. In the previous simulator SIMTRAVEL, the city is a squared, synthetic and regular city, useful for testing the starting hypothesis of the project indicated above. In the SANEVEC framework, a real city will be discretized into cells. Each city cell has a set of neighbors that are split into successors and predecessors. The cell state can be either occupied or non-occupied depending on its own state and on the state of its neighbors.

The vehicles are considered complex entities and are modeled as agents that incorporate complex behaviors, like decisions about the route to their destination, when to drive to a CS if the battery level is low, or which CS to choose. They occupy a cell and move around the city according to a finite state machine. Our model includes two types of vehicle agents: electric vehicles (EVs) and internal combustion engine vehicles (ICEVs). A third type of agents are CSs. Our focus lies on addressing traffic issues related to station location, EV movements, and time to recharge. Therefore, we take the assumption of underground CSs, because we do not aim to model a queue of vehicles accumulating outside a station. Thus, CSs are designed as unique road cells which do not occupy physical space and render vehicles inside them invisible to other traffic, with an assumption of unlimited parking for recharging and waiting vehicles. The vehicles inside a station employ a time to recharge that depends on the power of the chargers. If all the chargers within a station are occupied, a queue is formed inside the underground station.

A snapshot of the previous SIMTRAVEL simulator is shown in Fig. 2. It displays a fragment of the synthetic simulated city showing streets, avenues, roundabouts, vehicles (coloured dots), and one CS whose position is indicated by a red arrow.

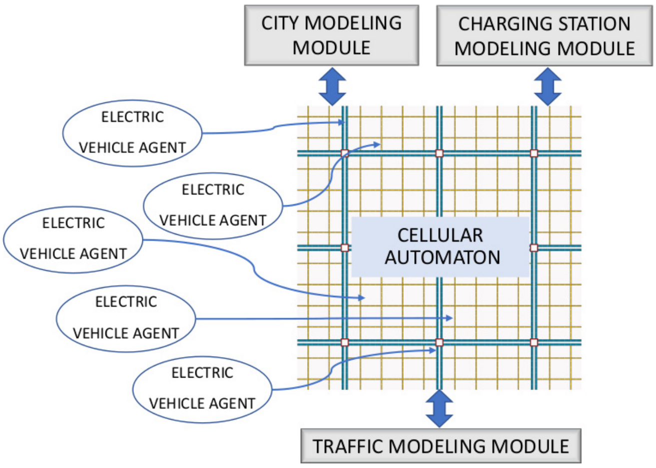

Fig. 1 Structure of the simulation model. It is a cellular-automata and agent-based microscopic hybrid model. The city is described as a lattice with cells, which can be occupied by a vehicle. Vehicles (EVs as well as ICEVs) are agents that can incorporate complex behaviors, and that move around the city. CSs are also another type of agent.

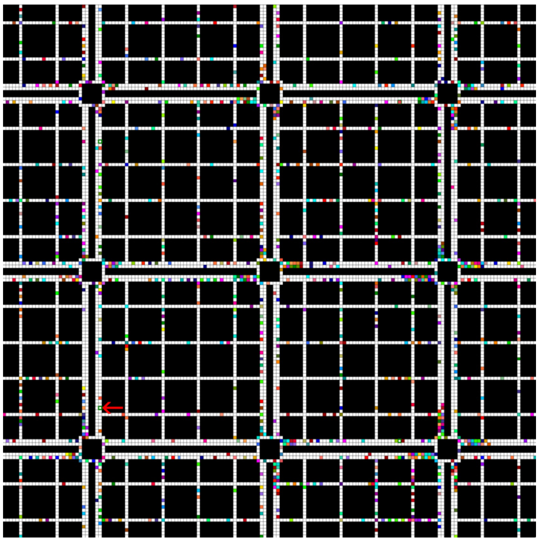

Fig. 2 Snapshot of a simulation with the previous simulator SIMTRAVEL. The image presents a section of the simulated city, illustrating streets, avenues, roundabouts, and vehicles represented by colored dots. The location of a charging station is highlighted with a red arrow.

As shown in [2], we studied using SIMTRAVEL the effects of different dispositions of CSs in a synthetic city, and found very different consequences for a large central station versus a set of smaller distributed stations.

For distributed CSs, the city reaches a stationary state in which the traffic is fluid and is homogeneously distributed, as shown in Fig. 3, that displays a heat map of the amount of traffic in the city after several hours of simulation.

On the other hand, for a single central large CS, we found that when the vehicle density exceeds a certain critical level, a large traffic jam that collapses the city is formed in a wide area around the central station, as shown in the heat map of Fig. 4.

In spite that the best layout is distributed CSs, we found a drawback: in the scenario of distributed CSs, EVs are not well balanced across the various stations, so some of them become saturated while others still hold free chargers. Accordingly, the average time spent by EVs queuing in the CS (that is, waiting for a free charger) gets higher than for a single large station when the vehicle density increases. As a consequence, it is very important to introduce smart routing measures to balance the distribution of EVs among the different CSs in a distributed network. These measures, which can range from placing information signs showing the occupancy level of each CS to implementing an intelligent traffic management system that directly interacts with the EVs or with their users, can be easily studied with the simulator that will be developed in the SANEVEC project.

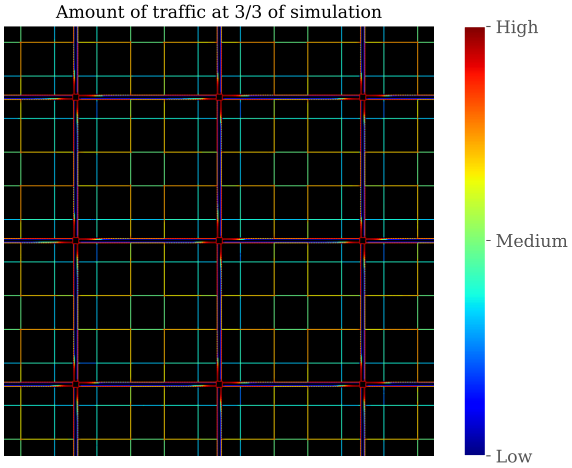

Fig. 3 Heat map of the amount of traffic in the city after several hours of simulation, obtained with the previous simulator SIMTRAVEL over a regular synthetic city, for a **set of distributed CSs**. The traffic flow is homogeneous and fluid.

Therefore, the previous work carried out with the SIMTRAVEL simulator showed that the simulator results were robust and meaningful, and demonstrated the key elements of the starting hypothesis of the SANEVEC project: i.e., that the location of charging stations alters traffic patterns in the city.

The SANEVEC project will extend the ideas tested with the SIMTRAVEL simulator to create a more complete and detailed model and will apply it to develop a complete simulation framework that works on real city data and involves a larger number of variables.

3.2 *Research objectives of the $SANEVEC$ project*

The specific objectives of the project are:

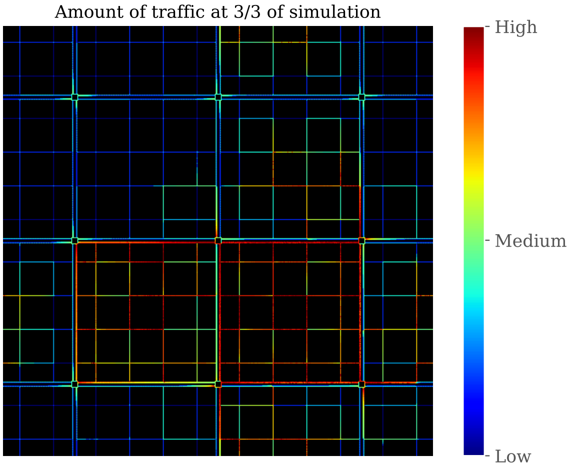

Fig. 4 Heat map of the amount of traffic in the city after several hours of simulation, obtained with the previous simulator SIMTRAVEL over a regular synthetic city, for a **single central large CS**. A large traffic jam that collapses the city is formed around the CS.

1. To develop a methodology to extract the geographic information from a real city using a geographic information system (GIS), and to inject it as an input of the city modeling module of a simulator.
2. To develop a simulator to predict the effects of a particular deployment of a network of charging stations on the traffic congestion, air-quality, carbon footprint and electric grid usage of a real city, derived from the SIMTRAVEL simulator that has already been developed for a synthetic city.
3. To develop a methodology to study the optimal deployment of the network of charging stations in a real city by simulations, using a genetic algorithm and the simulator developed in objective 2.
4. To develop methods and tools for the validation of the simulation results of the simulator developed in objective 2 and the analysis of its performance and scalability.
5. To test and validate the produced simulation framework, by developing an exemplary application to a particular city (Seville, Spain).

The project is expected to contribute to solve problems in the areas of ecological and digital transition, through environmental and social benefits:

- Regarding ecologic transition, the project will contribute to decarbonisation, energy efficiency, deployment of renewable energies, and electrification of the economy.
- Regarding digital transition, the project will have a positive impact in sustainable mobility and in the urban agenda.

4 Methodology

The structure of the framework for the optimal determination of the location of EV charging stations in a city is shown in

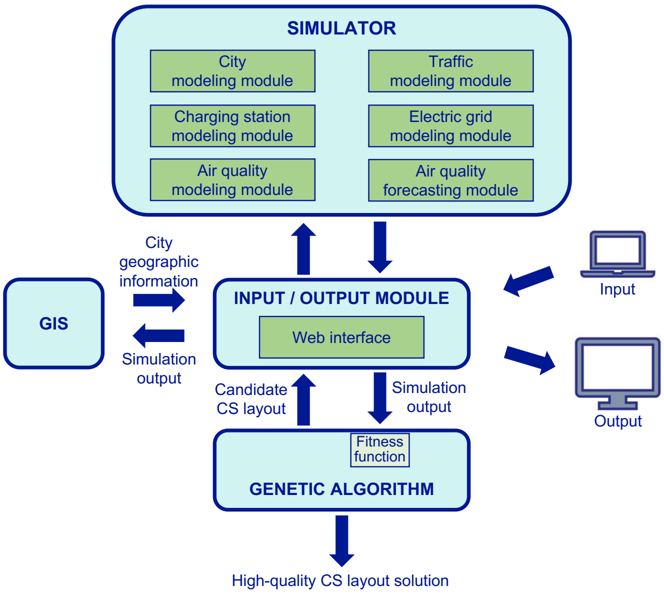

Fig. 5 Schematic view of the framework that will be developed in the SANEVEC project.

Fig. 5. There will be four main components: the simulator, the genetic algorithm module, the Geographic Information System (GIS) module and the input/output module. The simulator is the core component and is further divided into 6 modules.

The city modeling module will contain a model of the city to be simulated, obtained by a discretization of the geographical information of the real city. The traffic modeling module will be responsible for simulating the traffic of vehicles in the city. The charging station modeling module will contain the model of the behavior of a charging station: EV queue, time to recharge for a given outlet power, etc. The city, traffic, and charging station modeling modules will be based on the previous SIMTRAVEL simulator, as described in the previous section.

The electric grid modeling module will be responsible for simulating the operation of the electric grid in the city to which the charging stations are connected. It will take into account a simple model of the city electric grid composed of electric lines, buses, transformation units, loads, photovoltaic systems, and charging stations made up of several charging points. We plan to implement that module with an existing electric power distribution system simulator, such as OpenDSS [14], a free powerful software platform to simulate the distribution network, including support for distributed generation.

The air quality modeling module will be responsible for simulating the influence of traffic in the city on air quality, taking into account the operation of internal combustion engine vehicles and electric vehicles. It will employ the emission model of Panis et al. [15] to compute the instantaneous emission of each individual vehicle on every time step, and a cellular automata model such as [16], including rules for emission sources, diffusion and wind, for simulating air quality evolution in the city taking into account the dynamic traffic patterns.

The air quality forecasting module will be devoted to forecasting the air quality in the following few days, taking into account the results of the simulation from previous days. traffic data from previous days, using a Deep Learning artificial neural network model.

The GIS module will extract the geographic information from a real city employing a GIS and transform this information into a format understandable by the simulator.

The genetic algorithm (GA) module will use a GA for the optimization of the deployment of CSs. The GA will run an execution of the simulation of the city for a fixed period of time, using the simulator, for each particular deployment of CSs. After the simulation, the output of the state will be evaluated with some metrics that give a quantitative idea of the effectiveness of that deployment: traffic jams, average velocity of vehicles in the city, average waiting time for an EV to reach the CS, and to plug into a free charger, etc. A fitness function of the GA will be defined by taking into account the values of those metrics. The main reasons to choose a genetic algorithm for optimization are that this kind of algorithm is very well suited to obtain good solutions to optimization problems with a huge search space in a very reasonable time and that it is very well suited to be parallelized in order to reduce its runtime even more.

The modules will be developed using C++ programming language in order to obtain high performance in the execution of the tool. In addition, it is the best-suited language to parallelize the code to be run on high performance parallel computers, such as multicore systems with large core counts, clusters, or GPUS, by using OpenMP, MPI or CUDA, respectively.

The project will aim to achieve its objectives through seven work units, as shown in Fig. 6. The core of the project work is composed of work units dedicated to geographic information, simulator design and development, methodology to study the optimal deployment of charging stations through simulations, analyses, and application and validation. In addition, there are two transversal work units for management of the project and outreach: one of them is devoted to project management, and the other one to dissemination, exploitation, and communication plan of the results.

A proof of concept study for an exemplary application scenario to a real city will be carried out to validate the whole approach and its applicability in the real world.

5 Outlook and Expected Results

The transcendence of road traffic in cities is evident, and in summary it affects the climate, the environment, the economy, and people in general, from the time lost in travel to issues of vital importance such as human health (respiratory problems, stress, sedentary lifestyle, etc.). Many studies have shown the impact of urban pollution on health due to polluting vehicles and their influence on disease [17]. The popularisation of electric cars may be a good solution, but currently, the main problem is the lack of infrastructure to allow rational use of such vehicles. This is where the importance of this project lies: to foresee in a scientific way the best distribution of these

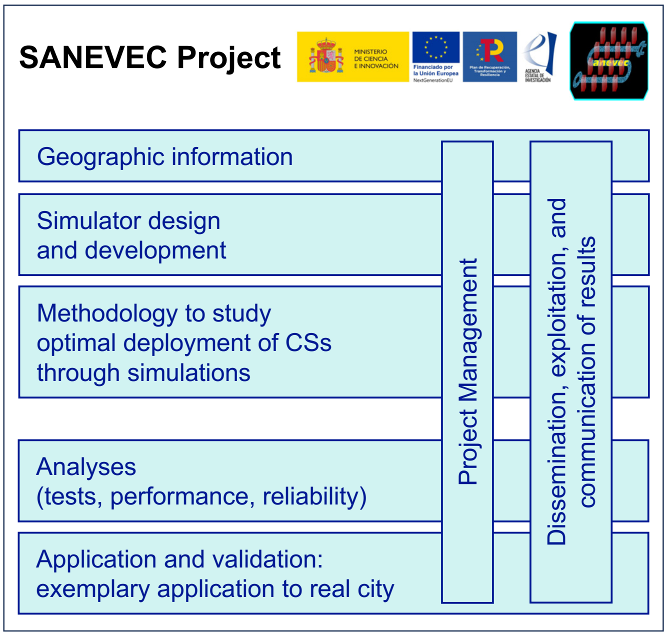

Fig. 6 Schematic structure of the SANEVEC project. There are 3 work units devoted to the design and development of the framework, plus 2 work units for tests and validation through an exemplary application and 2 transversal work packages for management and outreach.

electric charging infrastructures in cities. If this is not done properly, it can cause so many inconveniences that it can lead to the rejection of the electric car among citizens.

The impact of this issue is obvious, as decisions taken blindly in this area would end up having an impact on the chain of "traffic, climate, pollution, health". The implications are also economic: optimization of infrastructure costs, reduction of energy consumption by reducing the time between journeys, creation of jobs, etc. In short, it is vitally important, and probably urgent, to have tools that enable the right decisions to be made when deploying charging stations in cities.

For this reason, the framework developed as a result of SANEVEC will be made available to municipalities, governments, firms, research groups, and universities. The works and results of the project will be disseminated to local governments and to companies. We expect that the project SANEVEC has also an impact on the economic environment, by fostering innovation and economic activity in the field of transition to electric mobility.

Specifically, we expect that the project SANEVEC will contribute to the progress of our society by the following environmental and social benefits.

Expected environmental benefits:

1. Reduction of air pollution in urban areas, because of the reduction of traffic congestion and therefore in the number of polluting fossil fuel vehicles involved in traffic jams.
2. Reduction in the carbon footprint of cities due to the greenhouse gases.
3. Contribution to increase the proportion of EVs versus vehicles powered by fossil fuels, because of the improved user experience of EVs by reducing waiting times.
4. Reduction of noise pollution in urban areas, due to reduced congestion and quieter EVs.

Expected social benefits:

1. It will help the process of traffic electrification by optimising EVs charging operations. This will foster economic activity in the new sectors associated with electrification, contributing to economic growth and creating new skilled jobs for the population.
2. It will reduce transport times in the city, due to the reduction of traffic congestion.
3. It will contribute to increasing the quality of life of citizens, due to the combination of the aforementioned benefits.

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