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Transition to a Green Planet: Exploring Roadmap Designs for Electric Bus Transformation in Different Cities

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ABSTRACT

To mitigate the effects of the energy shortage and develop sustainability, governments are paying attention to the transformation of electric buses (e-buses) systems. Therefore, in this article, we develop a well-rounded conversion plan for 10 years that can be applied to a variety of cities. Ecological consequences are considered in the plan along with financial implications calculated by fundamental economic principles. Through an innovative use of the Markov Chain, we create a Survival Probability Matrix to precisely visualize the number of batteries consumed each year. Furthermore, by constraining the level of pollution of charging stations to the environment as well as maximizing the working efficiency of stations, we determine the optimum number of stations and their locations. We specify our model with the factors by taking individual bus routes and stations into consideration so that each route is planned to relieve the execution burden of local government. To gain results from our model, we adapt the Mont Carlo principles into our original Progressive Algorithm. Our model applies to three metropolitan regions: Helsinki, Perth, and Singapore. Utilizing the General Transit Feed Specification (GTFS) data provided by local officials, we graph the specific routes to be transformed annually and plot the ideal charging station locations.[1]

Introduction: The Rising Need for E-Bus

In response to the surging demand for energy consumption and the ongoing climate change, people delve into the realm of renewable energy. The record high carbon dioxide emissions of 34.4 billion metric tons in 2023 raise global awareness to address the emission issue caused by the staggering demand.[2] The governments put an emphasis on developing electric-based public transportation systems as a sustainable alternative to traditional fuel vehicles. In specific, the conversion to electronic buses (e-buses) serves a prominent role in the process. The New South Wales (NSW) government in Australia, for instance, has proposed to fully adopt a zero-emission bus fleet in Sydney by 2035.[3]

In this case, we focus on the adoption of e-buses into cities by designing a well-rounded 10-year provision roadmap to gradually facilitate the progress. The plan is then evaluated and further optimized concerning the ecological consequences and the financial implications. For ecological consequences, we investigate the e-bus fleet and charging station, respectively. Several factors (including noise, air, chemical, and water pollution from constructing and running an e-bus system) have been taken into consideration. For financial implications, we examine associated expenditures as well as the anticipated revenue yields. By doing so, we optimize the net profit and filter prospective external patrons to cover half of the cost. Lastly, we apply the model to three metropolitan regions (Helsinki, Perth, and Singapore) to verify its practicality.

Analysis of the Context of the Problem

Structure of Analysis

We will first clarify the structure of our analysis. Our solution to the problem presents an implication of the infrastructure assessment process for e-bus transitions. A ten-year roadmap will be the result of a thorough evaluation of e-bus-related endeavors to achieve ecological and economic stability in the metropolitan area the model aims to apply. The evaluation is comprised of two major criteria—ecology and economy—both of which commit to enhancing the feasibility and appropriability of the transition program.

1. Ecology
   In this particular aspect, we evaluate the project in terms of sound pollution, air pollution, and chemical pollution. The three factors would approximately simulate the full effect of e-bus transitions on the ecological system.
2. Economy
   We measure the economic effect of the current transition approach. The economic effect can be calculated by basic economic principles.
3. Planning
   Gathering the ecological and economic factors to compose an optimal roadmap that maximized both sides.

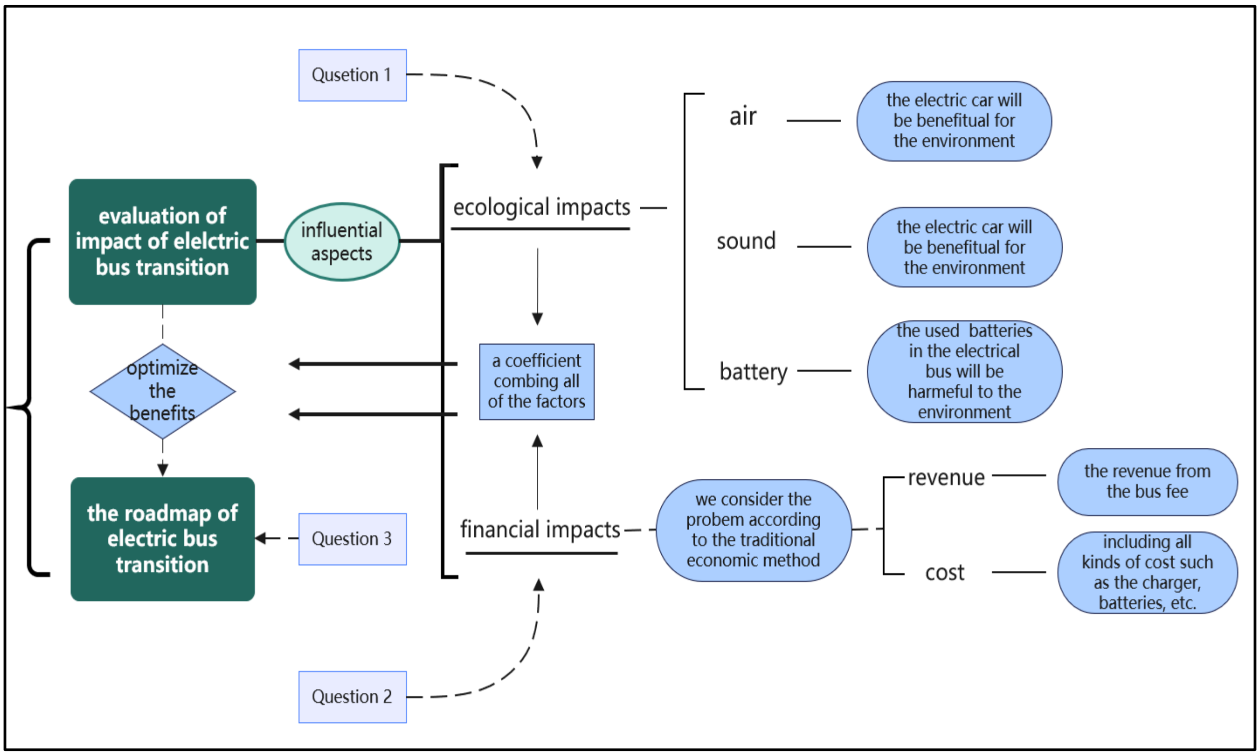

Figure 1. Research framework. Our research process strictly follows the paths above.

Assumptions and Definitions

General Assumptions

Assumption 1: Only one specific type of e-us is applied to the transition progress.

Justification: For city governments, the electrification progress can be better organized and monitored with one specific e-bus used. It avoids the incompatibility among different systems.

Assumption 2: Each electric bus charger has constant electric power supplied to the vehicles.

Justification: The variation in charging rate is negligible in real life.

Assumption 3: The number of buses, bus routes, and locations of stations remains unchanged in 10 years.

Justification: The electrification of public transportation systems tends to happen in developed cities and metropolitan regions. These regions will likely share the commonality of a low overall population growth rate. Hence, the demand for infrastructure remains constant over a fairly long period of time.

General Definitions

Variable	Definition
k_E	The ecological consequence indicator
k_F	The financial implication indicator
k_b	The ecological consequence indicator of bus operations
k_s	The ecological consequence indicator of charging stations
s	The sound pollution indicator of the e-bus transportation system
g	The gas pollution indicator of the e-bus transportation system
b	The chemical pollution indicator of the e-bus transportation system
r	The normalized total revenue gained through the e-bus
c	The normalized total expenditure of the transition progress

Methods

Ecological Consequence Evaluation Model

Considering the ecological impacts of the progress of bus electrification, multiple elements are attributed to such an indicator. Therefore, the model is developed with two components: the ecological indicator of bus operations and the ecological indicator of charging stations, which can be represented as the following:

$$k_E = k_b + k_s$$

where k_E is the overall ecological consequence indicator; k_b represents the ecological indicator of buses, and k_s represents the ecological indicator of charging station.

Ecological Consequences of Bus Operations

Hence, the ecological indicator of bus operation k_b can be derived from the subsequent formula:

$$k_b = s + g - b \tag{1}$$

where k_b is the ecological consequence indicator concerning the operation of buses. s, g, and b are the indicators of sound pollution, gas pollution, and chemical pollution, respectively. In the formula, normalization is used to avoid the unbalanced weighting caused by differences in dimensions as well as to improve the data integrity. Both indicators g and s, in this case, have a positive effect on the environment because of the elimination of noise and carbon dioxide emission in the transition of electric buses, while the indicator b, demonstrating the chemical pollution from disposal of battery, has a negative impact on the environment. To guarantee the positive correlation of k_e, indicator b should have a negative sign.

Sound Pollution Indicator: We set a sound pollution indicator to evaluate and quantify the change in noise. To simplify the calculation, we assume that all of the diminished noise pollution is uniform for every replacement of traditional buses with e-buses. It can then be concluded that the improvement of the sound environment is solely related to the characteristics of the bus route and the number of buses being transformed. In this way, can be defined as the following formula:

$$s = \sum_{j=1}^{m} n_j \times x_j^t \times r_j \tag{2}$$

where m is the number of the routes; x_j^t is either 0 or 1 to determine whether the bus on route j has been transformed on year t or not; n_j represents the number of e-buses transformed on route j, and r_j represents the characteristics of the corresponding bus route j.

We then further consider the characteristics of the route concerning multiple aspects: the population density, and the corresponding length of route respectively. As a result, the coefficient r_j can be calculated with the following formula:

$$\mathrm{r}_j = \sum_{i=1}^{n} \rho_i \times \mathrm{d}_i \tag{3}$$

where n represents the number of sections each bus route was divided into according to the population density; ρ_i represents the population density of each section; d_i represents the length traversed the corresponding population density section.

In this way, the final expression of s can be transformed into the following formula according to the explanation above:

$$s = \sum_{j=1}^{m} n_j \times (\sum_{i=1}^{n} (\rho_i \times \mathrm{d}_i)) \tag{4}$$

Air Pollution Indicator: The integration of electric buses into public transportation systems yields a favorable influence on the concern of air pollution. In contrast to traditional buses which burn fossil fuel, e-buses exhibit a notable advantage by achieving zero emissions of greenhouse gases during operation. It can then be concluded that the longer the aggregate daily distance covered by the entire e-bus fleet is, the more significant the mitigation of the gas pollution issue can be. Therefore, the air pollution indicator of electrification can be expressed through the ensuing formula:

$$g = \sum_{j=1}^{m} n_j \times d_j \times x_j^t \tag{5}$$

where g represents the gas pollution indicator of the entire e-bus transportation system; n_j represents the number of operating buses on each specific route j per day; d_j represents the distance of the route; x_j^t represents the decision variable, and m represents the total number of bus routes in the city chosen.

The augmentation of such an indicator implies a further address of air emission concerns, bringing a positive impact on the ecological system of the chosen city.

Chemical Pollution Indicator: Chemical pollution evaluation of the e-bus transition is measured by the number of batteries needed to be disposed of during the ten-year process.

$$b = \frac{N_b - \min(N_b)}{\max(N_b) - \min(N_b)} \tag{6}$$

$$N_b = \sum_{t=1}^{10} \mathrm{N}_t(1) \tag{7}$$

As shown above, the number of batteries needed to be disposed of, N_b, is calculated by $\sum_{t=1}^{10} \mathrm{N}_t(1)$, which is the summation of the first element of each year's battery matrix. We then normalize the value of batteries required for each possible combination of e-buses.

For every $\mathrm{E_t} = \sum_{j=1}^{m} n_j$, of each year, a matrix of batteries is separated into columns of different ages of use. $\mathrm{E_t}$ represents the extra number of buses converted in each year t. The first element is the number of batteries within their first year of usage. The second element is the number of batteries in their second year of use, and so forth:

$$N_0 = [0 \quad 0 \quad 0 \quad 0 \quad 0] \tag{8}$$

Then, the battery matrix for the same year is constructed as followed:

$$N_t' = [N_t(1) + E_t \quad N_t(2) \quad N_t(3) \quad N_t(4) \quad N_t(5)] \tag{9}$$

Considering the natural depreciation of vehicles, the battery has an increasing malfunction rate as their age of use increases. Therefore, the number of batteries needed can be modeled by the number of e-buses added to the city each year, and the possibility matrix is constructed as follows:

$$\mathbf{P} = \begin{bmatrix} \mathrm{br}_1 & \mathrm{sr}_1 & 0 & 0 & 0 \\ \mathrm{br}_2 & 0 & \mathrm{sr}_2 & 0 & 0 \\ \mathrm{br}_3 & 0 & 0 & \mathrm{sr}_3 & 0 \\ \mathrm{br}_4 & 0 & 0 & 0 & \mathrm{sr}_4 \\ \mathrm{br}_5 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{10}$$

The battery matrix for the next year thus, corresponds with our main formula:

$$N_{t+1} = N_t' \times \mathbf{P} \tag{11}$$

Ecological Consequences of Charging Stations

k_s is defined as the value of the ecological consequence indicator of the e-bus charging station.

Charging stations may emit pollution into surrounding water sources, so ecological friendliness increases as the distance between the station and the water increases. Meanwhile, if the charging station is too distant from the bus routes, it may not function as efficiently as expected. Combining all of the factors above, we can derive the formula:

$$k_s = \frac{l_{sw}}{\sum_{j=1}^{m} d\left(P_{s,j}, P_t\right) \times x_j^t} \tag{12}$$

where l_{sw} is the smallest distance between a charging station and the surrounding water source; m is the total number of bus routes, $P_{s,j}$, is the position of bus stops of route j; P_t is the location of the charging spot, and x_j^t is the decision variable.

The cartesian-coordinate system is used to simplify our expression. In this way, the distance between charging station and the water can be derived from the classic distance formula. The expression $d\left(P_{s,j}, P_t\right)$ can be clarified as follows:

$$d\left(P_{s,j}, P_t\right) = \sqrt{\left(x_{s,j} - x_t\right)^2 + \left(y_{s,j} - y_t\right)^2} \tag{13}$$

In the formula, $x_{s,j}$ represents the x-coordinates of the chosen bus stop j; x_t represents the x-coordinates of the station; $y_{s,j}$ represents the y-coordinates of the bus stop which is on route j; y_t represents the y-coordinates of the charging facility.

Financial Implication Evaluation Model

The financial ramifications stemming from the transition to electric buses are intricately linked to the overall program expenditure and anticipated revenue. By examining both factors, the city government can approach the optimum cost efficiency concerning the progression of the transition. Hence, the financial implications indicator k_F can be written as:

$$k_F = r - c \tag{14}$$

where r represents the envisioned revenue that will be generated from the converted e-bus system, and c represents the total cost of the electrification progress.

Revenue

The income of the public transportation system mostly comes from the tickets that passengers purchase on individual routes. Accordingly, within the context of the e-bus transportation system, we anticipate that ticket revenue is the sole contributing factor. As a manufacturing project constructed to elevate the living standards of citizens, the e-bus system is expected to charge a constant price over a long period of time. The total revenue earned would be directly proportional to the number of passengers. The formula that expresses the aggregate revenue of the e-bus fleet can be written as:

$$r = \sum_{j=1}^{m} N_{p,j} \times \mathrm{P}_t \times r_j \times x_j^t \tag{15}$$

where $N_{p,j}$ represents the anticipated number of passengers on the respective route j; P_t represents the ticket price sets by the local government; x_j^t is the 0 or 1 decision variable, and m is the number of e-bus routes.

Cost

The cost associated with the transition to e-buses encompass a multitude of factors that necessitate a thorough examination. Initial considerations involve upfront expenditures linked to the procurement of e-buses. E-buses need to be purchased to displace the current fossil fuel-charged fleet.

In addition to bus acquisition costs, infrastructure expenses must be taken into account. This includes the installation of charging stations and chargers, which often require substantial investments.

Operational costs constitute another crucial aspect of the e-bus transition. While e-buses offer reduced fuel costs compared to traditional buses, ongoing expenses such as electricity consumption and maintenance such as battery depreciation and replacement must be factored in.

Therefore, the cost of electric consumption can be simplified into the following formula:

$$c = c_b + c_u + c_e + c_c + c_t \tag{16}$$

The cost of the battery could be directly measured through the battery matrix discussed in 4.1.1.3:

$$c_b = N_b \times \mathrm{P}_b \tag{17}$$

where N_b denotes the number of batteries consumed, and P_b stands for the unit price of the battery.

The cost of the e-bus can be written as:

$$c_u = N_u \times \mathrm{P}_u \tag{18}$$

where N_u is the number of buses purchased, and P_u represents the unit price of e-bus.

Electricity cost could be calculated from a different angle from the electricity usage of charging stations since this is statistically difficult to achieve.

$$c_e = \sum_{j=1}^{m} l_j \times \frac{\mathrm{Q}}{\mathrm{S}} \times n_j \times \mathrm{P_e} \tag{19}$$

In this formula, l_j stands for the length of each route numbered by j; Q, the capacity of the battery, divided by S, the maximum distance to empty the e-bus, which the ratio represents the amount of electricity consumed per unit distance, with n_j as the number of e-buses.

The cost of the charger could be simply given by the following equation:

$$c_c = n_c \times \mathrm{P_c} \tag{20}$$

The equation has n_c as the number of chargers in the station multiplied by the price of each charger.

The cost of estate price factors a majority of the cost of a charging station. Charging station costs could be approximated by the estate cost of the station. Therefore, we arrived at this equation:

$$c_t = (n_c \times \mathrm{A_c} + \mathrm{A_s}) \times \mathrm{P_a} \tag{21}$$

In the equation, the charger stands for the parking area for each charger and the standard area of each charging station.

Prospective External Funding Resources

The electrification of bus vehicles typically entails higher initial costs compared to conventional diesel or gas-powered buses due to their advanced technological features and battery systems.

Within the domain of construction and maintenance expenditures, the implementation of a Public-Private Partnership (PPP) serves as a viable strategy to cover half of the total cost. The government can split the bill with the private sector by providing them with future returns or non-financial benefits.

Bus, Battery & Charger Cost: Considering the construction and maintenance expenditures, it is possible to cover half of the total cost by submitting public bids for each section. The flourishing electric vehicle (EV) corporations are prospective investors to contract for the conversion of e-buses, the construction of charging stations, as well as future operation and depreciation expenses.

To be specific, well-developed EV manufacturing companies have an inclination to invest in government-led construction projects. BYD, for example, has announced plans to further develop the EV market in Japan with its middle-sized e-bus products in November 2023.[4] The buses will be sold to meet the increasing demand for local green public transportation. By doing so, corporations are exposed to potential markets as well as automatically being credited by authoritative governments. The manufacturing corporations can provide cities with the e-buses and batteries required during the progress to substitute for the costs of purchasing new e-buses by the government throughout the next 10 years.

Electricity Cost: Even though infrastructures like the e-bus fleet are not expected to be profitable, passengers are charged to cover the operating costs of the system. By setting a reasonable ticket price, the city government can compensate the operation expenditure with a portion of the generated ticket revenue.

Station Cost: Station construction costs are generated by the land rent concerning the amount of land utilized as well as the price of the land. Since the conversion of the e-bus fleet is a government-led program, the estate cost should be evaluated based on specific national policies towards land ownership. If the land is owned by the government of the country, there should not be estate costs derived in this case. On the other hand, if the land to be used is the private property of citizens, the government is required to compensate the landowner while condemning the area with the power of eminent domain or expropriation actions. Therefore, without severely polluting water sources nearby, it is suggested to utilize public lands prior to privately owned regions to reduce costs. The government can offer future returns to landowners in exchange for charge-free usage.

Roadmap Design Model

To derive an optimal roadmap, we need to maximize the positive impact of every step so that the integral results can reach their maximum according to our model. We define the indicator k to show the final comprehensive positive impact of transformation in one year. The k value will integrate all of the indicators we consider in former models.

Also, besides the demand for maximized k, there are several factors that needed to be considered: the total number of traditional buses should equal the total number of transformed electric buses; the number of transformed buses annually should be more than 20. Thus, k can be calculated through the following formula:

$$\max\{k = k_F \times k_E\} \tag{22}$$

$$s.t.\begin{cases} \boldsymbol{N}_{\mathrm{T},m} = \begin{bmatrix} n_{1,1} & n_{1,2} & \cdots & n_{1,m} \\ n_{2,1} & n_{2,2} & \cdots & n_{2,m} \\ \vdots & \vdots & \vdots & \vdots \\ n_{\mathrm{T},1} & n_{\mathrm{T},2} & \cdots & n_{\mathrm{T},m} \end{bmatrix} \\ \sum_{t=1}^{\mathrm{T}} \sum_{j=1}^{m} n_{t,j} = \mathrm{n_{tot}} \\ \forall\, t \in [1, \mathrm{T}]: \sum_{j=1}^{m} n_{t,j} > 20 \end{cases} \tag{23}$$

where k is the final integral indicator we aim to maximize; k_F is the financial impact derived from the former model; k_E is the ecological impact derived from the former model. $\boldsymbol{N}_{\mathrm{T},m}$ is the matrix that represents the number of buses need to be transformed on each route j on year t; T is the constant symbolizing 10 years duration; m is the constant representing the total bus routes needing transforming; $n_{t,j}$ represents the number of cars required to be converted at the year t on route j, and $\mathrm{n_{tot}}$ represents the total number of transformed buses.

Model Applications

Roadmap Design of Helsinki: The Lahdenväylä→Kalastajantie Plan

Our plan in Helsinki starts at Lahdenväylä in year 1 and ends at Kalastajantie in year 10. Helsinki has demonstrated a steady rate of growth in its economy over the years. One of the key factors contributing to this is the city's diversified and resilient economy. Helsinki has successfully transitioned from traditional industries to a knowledge-based economy, with a strong focus on technology, innovation, and research. This diversification has helped the city mitigate the impact of economic fluctuations and maintain a consistent growth trajectory.[5] Meanwhile, Helsinki's resilience is closely tied to sustainable development. By complying with the creed of green development, the whole city can keep its development constant and relentless.[5] Thus, maintaining the current development standard is also necessary.

Given the situation of Helsinki, we can use our model to solve the solution by balancing the value k_E and k_F while maximizing the negative k value. In other words, the weight of k_E and k_F in our model and program, in this case, is equal.

With the restrictions described above, we can apply the Progressive Algorithm[6] to deal with mass data in Helsinki.[7] In particular, we random the matrix $N_{t,j}$ for a large number of times, and then compare and select the more promising one among all. Therefore, $N_{t,j}$ can be calculated, and the result is shown below:

Applying the data of Helsinki, we can derive:

indicator	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	average
chemical	0.349514563	0.322430258	0.335235128	0.291195088	0.32106966	0.247106278	0.315364752	0.090761958	0.167472033	0.241161903	0.731869
gas	0.814595619	0.791756579	0.879948072	0.814575533	0.906581431	0.951243176	0.961788968	0.963735608	0.943544171	0.934112551	0.896188
sound	0.613629238	0.629739228	0.660922878	0.615164511	0.691595021	0.784649021	0.78570477	0.771946222	0.718532104	0.707415722	0.69793
kf	0.264114675	0.30730897	0.325687749	0.323969423	0.370525361	0.537542743	0.470340018	0.681184264	0.551060071	0.466253819	0.429799
ke	1.078710293	1.099065549	1.205635821	1.138544957	1.277106792	1.488785919	1.432128986	1.644919872	1.494604242	1.40036637	1.325987
k	0.636824885	0.747438513	0.874113057	0.860097144	0.969809063	0.947525185	0.84305823	0.953163177	0.859018063	0.896633017	0.858768
revenue	0.613629238	0.629739228	0.660922878	0.615164511	0.691595021	0.784649021	0.78570477	0.771946222	0.718532104	0.707415722	0.69793
cost	0.349514563	0.322430258	0.335235128	0.291195088	0.32106966	0.247106278	0.315364752	0.090761958	0.167472033	0.241161903	0.731869

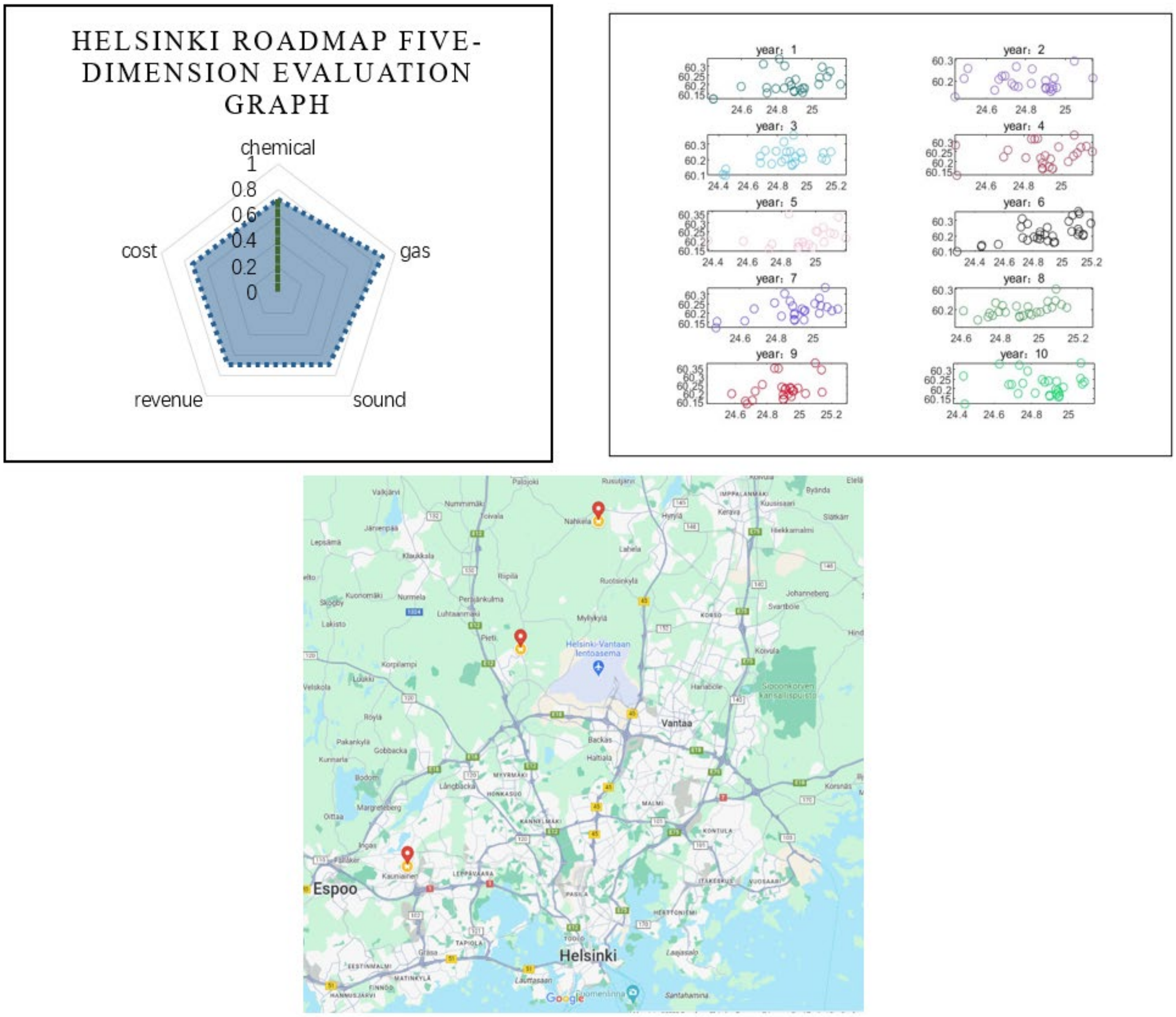

Figure 2. Results of Helsinki. The graph on the top left presents the normalized data of each indicator ranging from 1 to 0 of our plan in Helsinki. The graph on the top right presents the coordinates of transitioned bus routes each year in Helsinki, with the x label representing longitude, and the y label representing latitude. The red marks on the map at the bottom represents the location of the chosen charging station[8].

Roadmap Design of Perth: Werribee Rd. →S Yunderup Rd. Plan

Our plan for Perth starts at Werribee Rd. in year 1 and ends at S Yunderup Rd. in year 10. We analyze Helsinki and design the roadmap in a quite balanced way by making the financial and ecological aspects have the same weight. However, Perth faces environmental challenges like water scarcity, biodiversity loss, poor air quality, waste management issues, and climate change vulnerability.[5] Sustainable practices are needed to protect the environment. Efforts are underway to address these challenges and create a greener future for Perth. Therefore, in Perth, the roadmap would put much emphasis on the ecological impact of a particular roadmap.

In this case, we can slightly change our model to fit into the specific situation for every country. Instead of having the same weight for each indicator we make, we can assign the weight for each indicator. For example, we will adjust our program to use another way to process the data about ecological consequences and revise the calculation k_s so that the final result can fit into the requirement the city potentially wants to reach.

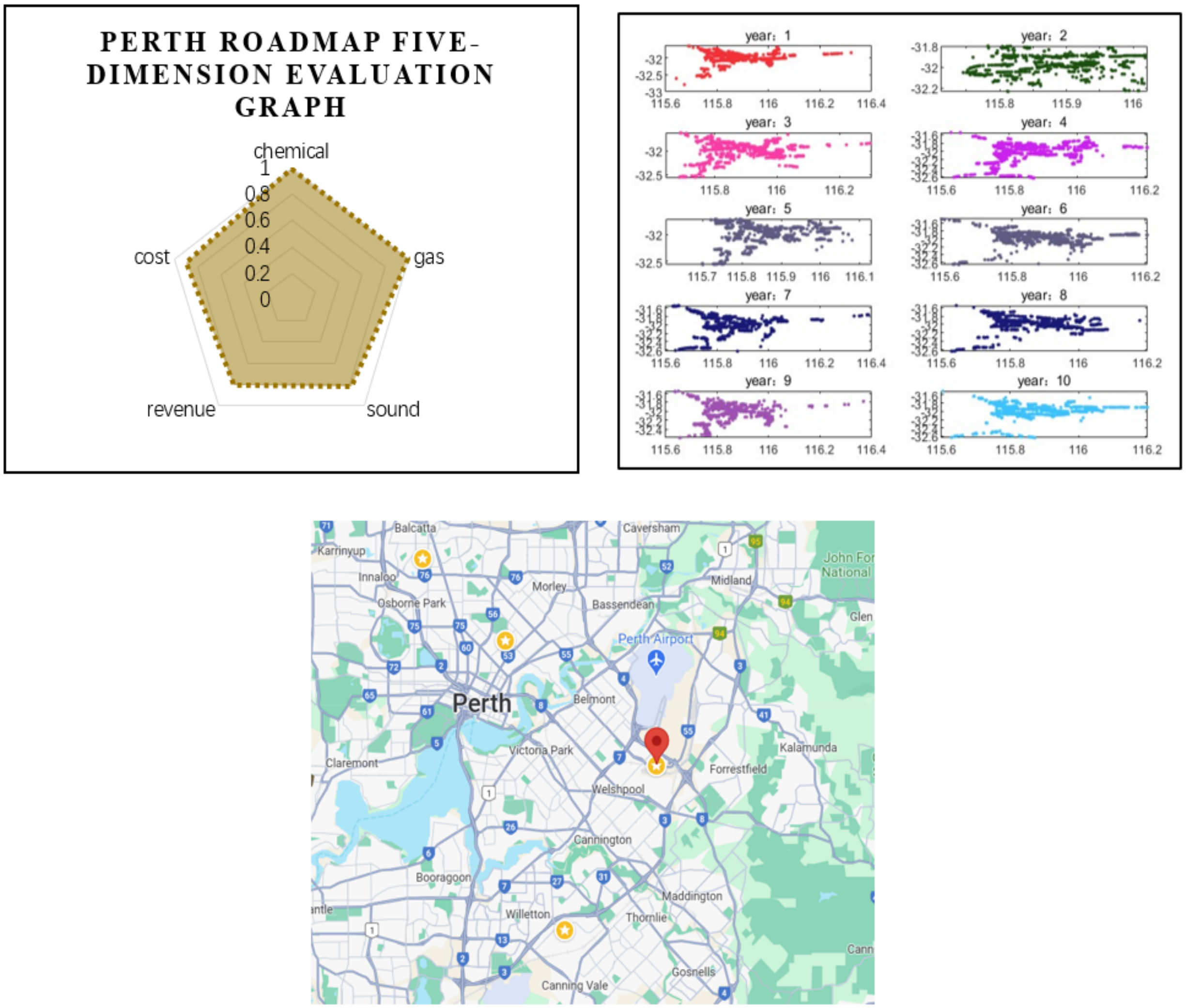

Figure 3. Results of Perth. The graph on the top left presents the normalized data of each indicator ranging from 1 to 0 of our plan in Perth. The graph on the top right presents the coordinates of transitioned bus routes each year in Helsinki, with the x label representing longitude, and the y label representing latitude. The yellow marks on the map at the bottom represents the location of the chosen charging station[8].

Roadmap Design of Singapore: Jln. Ahmad Ibrahaim→Pasir Ris Drive Plan

Our plan for Perth, starting at Werribee Rd. in year 1 and ending at S Yunderup Rd. in year 10, considers several factors. In Singapore, land scarcity and high living expenses are well-known challenges, and constructing charging stations for e-buses may require significant land and labor resources.[5] Therefore, it is crucial to optimize the use of construction lands to ensure cost efficiency. However, Singapore has a history of sustainable development, and its ecological condition is highly regarded globally, indicating that any short-term side effects can be minimal. Moreover, implementing an e-bus program in Singapore offers strong economic benefits, including long-term cost savings, operational efficiency, and scalability potential. These advantages make it an attractive investment opportunity for external funders seeking financially sustainable projects. Therefore, the focus in Singapore would likely be on the financial implications rather than the ecological consequences, attracting multiple external funders and emphasizing the profitability of the program.

Given the situation of Singapore, k_f is superior to the indicator k_f while maximizing k value. In this way, the weight of k_e and k_f in our model and program should have a favor on k_f.

Thus, the ultimate 10-year plan we design for Singapore is:

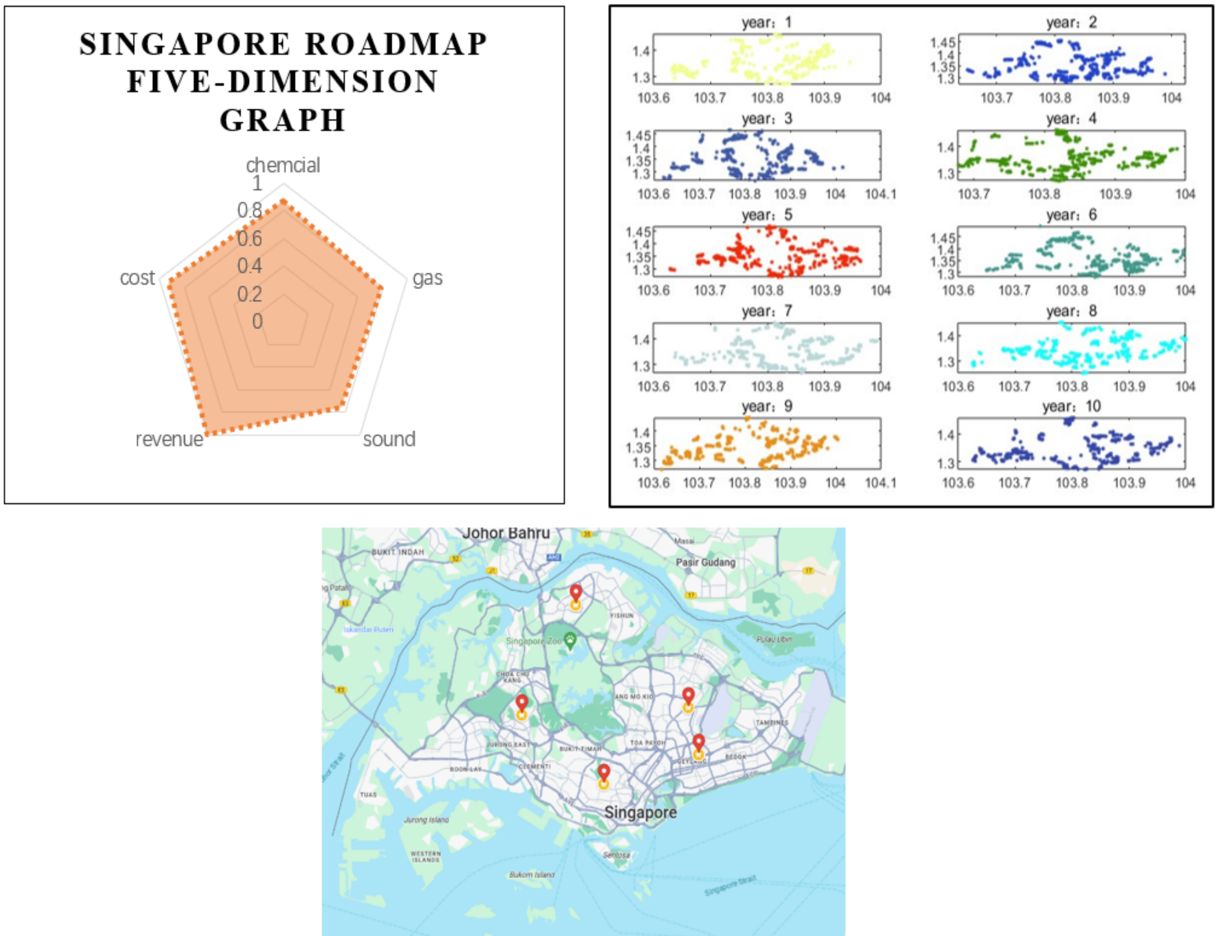

Figure 4. Results of Singapore. The graph on the top left presents the normalized data of each indicator ranging from 1 to 0 of our plan in Singapore. The graph on the top right presents the coordinates of transitioned bus routes each year in Helsinki, with the x label representing longitude, and the y label representing latitude. The red marks on the map at the bottom represents the location of the chosen charging station[8].

Conclusion

In conclusion, our model aims to develop a comprehensive plan of urban transitions towards an e-bus operation system within 10 years. Two major indicators, ecological consequences, and financial implications, are examined to optimize the plan. The Progressive Algorithm is applied during the realization to generate an elaborated annual plan for Helsinki, Perth, and Singapore with each unique demand accordingly.

Year	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Number of Buses	430	456	421	390	440	447	431	419	441	452

According to the table, e-buses replaced each year in Helsinki generated by our model are consistent with the requirement of the stable growth of the city.

In the prospective future, our model can be updated in line with the envisioned technological advancement in the field of electric-charged automobiles and improvements in the operational expense. The results will be further reinforced with higher accuracy to be implemented in a wider range of metropolitan regions.

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