Concordia Institute for Information System Engineering (CIISE)

ENGR 6991

Project and Report
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Electric Vehicle Charging Network ROI Optimization using AnyLogic

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Abstract

This report follows the research of a multi-agent-based system in developing an electric vehicle charging system and its optimization using previously conducted research and whitepapers. This paper chronicles the evolution of a proof-of-concept model designed to address an optimization challenge: strategically positioning electric vehicle charging stations to maximize return on investment. AnyLogic is utilized to conduct this research, and libraries within AnyLogic were used for mapping roads and infrastructure.

1. Introduction

The climate crisis coupled with the growing popularity of electric vehicles in Canada has led federal and provincial governments alike to incentivize the adoption of electric vehicles. This is further associated with several socioeconomic factors that may impact the growth of this EV network. For the purposes of this project, we will follow how to optimize the charging network and placement of charging stations for said EV adoption. There are several socioeconomic factors that may impact EV adoption such as government incentives, economic considerations, income and affordability, urban vs rural divide, and the charging infrastructure.

1.1 Problem Statement

As the number of EVs on the road continues to rise, the need for a robust and efficient charging infrastructure becomes paramount. However, the optimal placement of Electric Vehicle Charging Stations (EVCS) and its return on investment is a complex challenge, influenced by factors such as user demand, geographical considerations, and urban planning. This project aims to address this challenge by leveraging the power of simulation and optimization through the use of AnyLogic, a cutting-edge multimethod simulation tool. By integrating advanced modelling techniques, real-world data, and optimization algorithms, the project seeks to provide a comprehensive solution for strategically placing EV charging stations to enhance efficiency and return on investment. AnyLogic simulation will help us to plan, design and optimize the placement and number of chargers to be placed.

1.2 Project Scope

This project follows the analysis of tools, all the way to the development of a multi-agent-based model of the electric vehicle charging station network. For the purpose of this project, we are modelling different parts of the city of Montreal, located in Quebec, Canada.

This project aims to serve as a proof-of-concept model for larger research projects that aim to optimize EVCS networks.

1.3 Simulation Questions

1. Does the placement of chargers have an impact on the rate of return on investment?
2. What is the optimal number of chargers for electric vehicles on the road?
3. How to improve the rate of return on investment of a charging network?

2. Multi-Agent-Based Systems (MAS)

Multi-agent-based systems (MABS) are a computational framework used to model and simulate complex systems. Each agent in an MABS represents an individual entity that can

perceive its environment, make decisions based on rules or algorithms, and interact with other agents. These interactions lead to emergent behaviours and patterns at the system level, which can be analyzed to gain insights into the behaviour of the overall system.

2.1 Advantages of using multi-agent systems to simulate socio-economic scenarios

Socio-economic systems are inherently complicated due to the large number of interacting actors and the dynamic interactions that exist within them. MABS offers a framework to effectively capture this complexity, enabling a more accurate representation of socio-economic events that occur in the actual world. Multi-agent systems make it possible to investigate how interactions between individual agents might result in larger patterns and consequences. This is especially useful for comprehending how macro-level patterns and phenomena result from interactions between micro-level agents.

Nowadays, several incredibly sophisticated tools are on the market that are able to simulate such systems and represent complexity accurately, allowing a more realistic portrayal of real-world socioeconomic phenomena. Researchers and analysts can use MABS to test hypotheses about how specific factors or agent behaviours contribute to socioeconomic outcomes. This can help identify causal relationships and mechanisms underlying complex systems.

These also allow for the creation and exploration of what-if scenarios. This is valuable for businesses, governments, and organizations that want to prepare for a range of potential future developments and adapt their strategies accordingly. Furthermore, simulating socio-economic scenarios with MABS can help assess and mitigate risks associated with various economic, social, or environmental factors. It provides a platform for understanding vulnerabilities and developing risk management strategies.

MABS can also be used to optimize resource allocation in socio-economic systems, such as workforce management, supply chain optimization, or infrastructure development. It can help identify efficient allocation strategies and reduce wastage. They can model market dynamics, including supply and demand, price fluctuations, and market power. This is valuable for industries like finance, where understanding market behaviour is crucial. In addition, in other sectors like healthcare and urban planning, multi-agent system simulation can be used to optimize resource allocation, such as hospital beds, transportation networks, or educational facilities, to meet the needs of a growing population. Decision-makers in various domains can use these simulations to make informed decisions that account for the complexity and uncertainty inherent in socioeconomic systems. Such systems may also be used to evaluate how various policies or interventions would affect socioeconomic systems. Policymakers can test different policy scenarios by modelling.

Overall, simulating socio-economic scenarios as multi-agent systems provides a versatile and powerful approach to understanding, analyzing, and improving complex socio-economic systems, making it a valuable tool for researchers, policymakers, and organizations.

3. Review of existing tools and technologies for MAS

The project take-off included reading an extensive review of major MAS platforms and analyzing which would be best suited for the scope and purposes of this project. This was conducted using the *'Agent Based Modelling and Simulation Tools*' (Abrar et al., 2016), paper as a basis, to build off of using our own discussed criteria.

Eighty-five different MAS tools are discussed in this paper, of which five were shortlisted for analysis, to be able to select the best-suited tool for this project. These shortlisted tools included: AnyLogic, NetLogo, UrbanSIM, MatSim, and MASS.
The criteria for evaluation of these five tools were: the scale at which it can model, the usage domain, user-interface and simulation animations, ability to simulate socio-economic phenomena, computing resources required for large-scale projects, online resources available, personal preference, as well as artificial intelligence connection or integration. The results of this can be seen in **Table 2** in the appendix.

4. Literature review

The journal article on Agent-Based Modelling and Simulation by JASSS, defines multi-agent-based systems as, 'an abstract and simplified representation of given reality, either already existing or just planned. Models are commonly defined in order to study and explain observed phenomena or to foresee future phenomena'. (Bandini et al., 2009)

4.1 White papers

AnyLogic has several whitepapers and projects done on different MAS projects. Of those a few were selected and utilized as further relevant literature for this project.

4.1.1 Electric Vehicle Driver Simulation using Agent-Based Modeling AnyLogic

This white paper decides on complexity by dividing types of trips into two separate types: commuting and daily errands. The agents were equipped with a statechart-based planning engine: in each daily planning cycle, each agent first decides whether to commute versus run errands. This choice is made, and the agent then plans what trips will be taken that day with the electric vehicle. For commuter agents, this will usually just be an outbound and an inbound trip, but the distance, destination and timing will vary. For errand-running agents, decisions must be made around destinations, duration of time spent there, and how many to visit in one trip versus separate trips.
(Kock, 2014)

4.1.2 Modeling of Municipal Electric Vehicle Fleets

SimPlan published this whitepaper based on the German city of Hanau, and the electric fleets of municipal vehicles, mainly buses and trucks. Among the challenges faced was the

travelling distance, where a conventional diesel vehicle can cover 500km, these can only cover between 300-350 km. Along with travel distance, another factor considered was temperature, as the weather affects the vehicle.

The problem is that the EV travel range is less than the public transport's current tour distance. Consequently, vehicle schedules and routes would need to be adjusted for the new EV-based fleet mix.

Secondly, the charging process is non-linear. How quickly an electric vehicle charges depends on its state of charge, the amount of power available at the charging stations, and the number of vehicles charging at the same time.

In this project, SimPlan specialists built models of municipal electric vehicle fleet operations. In the models, they considered two vehicle types: buses and garbage trucks (both conventional, battery- and fuel-cell-powered) and modelled them as agents. To accurately describe the systems' behaviour, they used AnyLogic statecharts and Java for heuristics development.

The company used simulation modelling because it can accurately forecast large-scale EV fleet tasks and assess their daily operation.

(SimPlan)

4.1.3 GE Electric Vehicle Transportation and Charging Network Analysis

Global Research published this whitepaper with AnyLogic, for their research on the EV charging network. It tracked the transition of an agent from being a potential buyer to a user of either an EV or ICE vehicle.

The team at GEGR, modelled adaptive driver behaviour, such as when a driver takes an extended journey (as opposed to a regular home-work-home route) and needs to decide when and where to charge. Additionally, potential EV buyers might have very different priorities due to variables such as income, commute distance, personal preferences, and so on.

Two separate approaches were tried in this whitepaper, a granular model approach that simulated the process and used the Example-Based Evidential Reasoning (EBER) approach. This allowed the forecasting of how multiple factors could influence people's decisions. The approach was developed by GE and has been used in several projects related to risk management and competitive pricing. The second was a charging network simulation.
(General Electric Global Research)

5. AnyLogic tools and libraries

AnyLogic is a multi-method modelling tool that supports discrete, agent-based, multi-agent-based, and system dynamics simulation projects of a large size. It also allows a combination of these types of simulation models. A main usage of AnyLogic is simulation analytics. It allows the creation of large, complex simulation models based on the exact functioning required, as well as a sophisticated graphics system that allows a real-life simulation to be observed, alongside simulation values and statistics. These visualization and animation tools in AnyLogic make it a great tool for technical and non-technical customers alike, leveraging the technical functionality to develop highly complex projects and discuss findings with customers and show impact not only through numbers but also through animations in 2D as well as in 3D.

AnyLogic provides allows users to simulate real-world problems in risk-free environment prior to practical implementation to see results in a tangible way. The ability to simultaneously model several real-life factors provides increased accuracy, as well as accounts for uncertainty.

The software uses the Java programming language. Models created with AnyLogic are fully extensible at the Java level, with the option to create Java objects as classes, and define custom functionality. Component functionality can be further customized by adding Java code in the ‘Advanced’ section of the ‘Properties’ of each component. It also allows the usage of data from external sources such as a database or a Microsoft Excel file.

Furthermore, AnyLogic allows the creation of one’s own libraries, as well as extend and import other existing previously created libraries; the integration of machine learning algorithms is a great win for the software.
The software also allows the integration of a python library that proves useful for simulation, by the name of ‘PypeLine’.

5.1 Features and Libraries

AnyLogic contains a multitude of industry-specific libraries to model different situations. For the purposes of this project, the libraries are mentioned below in the remaining part of this section.

5.1.1 Animation Library

The animation library is built into the AnyLogic software. It allows the conversion of flowcharts into interactive movies with 3D and 2D graphics.
The objective is to present models to stakeholders in a visually appealing and self-explanatory manner, utilizing an extensive array of graphical objects. These objects are designed to vividly illustrate various elements such as vehicles, staff, equipment, buildings, and other pertinent aspects of business processes. There is capability to import custom 3D models, images, CAD drawings, and shape files further enhances the flexibility of

simulations. Additionally, you can incorporating intuitive navigation and controls to make the models interactive. Finally, it underscores the conversion of simulations into comprehensive management dashboards, offering a holistic approach to visually represent and manage complex business scenarios.

5.1.2 Geographic Information System (GIS)

AnyLogic introduces a distinctive feature by enabling the incorporation of Geographic Information System (GIS) maps into simulation models. This functionality proves particularly valuable for modelling complex systems such as supply chains and logistics networks, where considerations of locations, roads, routes, and regions are essential. The platform offers a built-in search feature akin to Google Maps, simplifying the location of cities, streets, roads, hospitals, shops, and bus stops using map data. This search functionality operates seamlessly during both the model design phase and runtime. Notably, model elements can be strategically placed on the map and navigated along existing roads and routes, leveraging real spatial data for enhanced realism. AnyLogic provides the flexibility to utilize free maps, accessible online or offline, or opt for tile- or shapefile-based maps from preferred external providers.

(*Features – AnyLogic Simulation Software*)

5.1.3 Analysis

AnyLogic provides data analysis features that update at run time and can be configured to use existing data or data at simulation run time. There is the ability to add different types of charts for analysis, such as a bar chart, histogram, pie chart, time series, etc.

5.1.4 Agent

The AnyLogic software contains a palette for agent-based simulations which allows you to create agents, of any agent type, including custom types. It also contains functionalities to further customize your agent, or agent-class, which is defined as a Java class, with the help of parameters, variables, and functions. An agent class can also inherit another agent class, thus enabling Java superclass functionality.
The agent palette also contains the functionality to define state charts for agent classes, which define the states an agent object belonging to the specific agent class can be in. Java code for further customization can be added to any of the states, and transitions.
Furthermore, an event can be added, which can trigger the creation, updation or deletion of any given attribute, variable, etc.

6. EV project configuration and setup

The use of superclasses, classes and objects in object-oriented programming allows this project to be incredibly modular and by extension, incredibly scalable and adaptable. The project has been completed in AnyLogic 8.6.6 Personal Learning Edition. The final code and

end to end workings can be found in the appendix of this document. The entire code can be saved to a file with an *.alp* extension, and run in AnyLogic 8.6.6 or greater.

6.1 Class Diagram

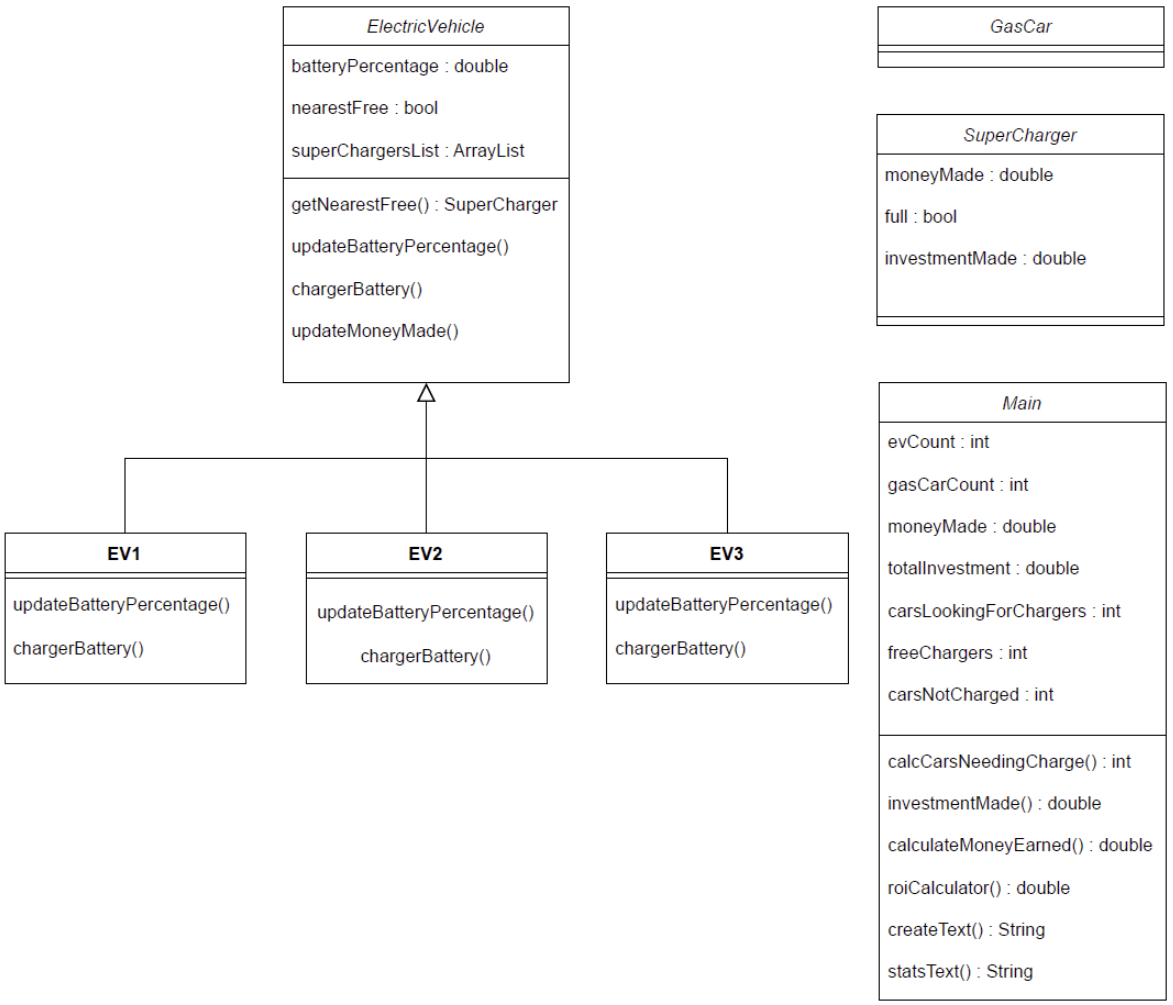

Image 1: Project class diagram.

6.2 Assumptions

As this project is a proof-of-concept model, real values are not used, rather are assumed, thus the model may not replicate the exact values and times, but will replicate the exact workings in a real-world scenario.
For the sake of ease and time, the model worked with model time units, so the scenario is not too slow, or too fast, as it would be if model time units were set as seconds or as hours respectively.
For the purposes of this model, a major assumption was that all electric vehicles will start off with a 100% battery charge, and also are at good battery health, so all objects of a specific type of EV, will lose charge at roughly the same rate.

A major assumption is that all electric vehicles are charged at only these superchargers, and an electric vehicle does not leave a charger until it is fully charged. This makes the system a bit more stringent, as in the real-world cars may leave before they are fully charged, and chargers may be available in other locations too.

6.3 Project set up

On AnyLogic startup, a new project was created. AnyLogic allows you to pick model time units, that it will then use to simulate the scenarios. As mentioned above, the model time unit was set as minutes.

6.4 Agent types created

AnyLogic does not contain any agent types of electric vehicles, so those were the first to be created, along with gas cars and superchargers.
AnyLogic allows the usage of existing agent classes, that may be regularly needed and used, however, for the needs of this project we will create our own agent types. Once an agent type is created as a Java class, its specific parameters, variables and functionalities can be defined, as well as statecharts that will apply to all the agents (objects) created of that type.
Following this, an agent population can be created and used.

6.4.1 GIS Map

The first step in this project would then be to pull in a GIS map element from the GIS library and place it in the main project area. The built-in search feature is used and the map is zoomed, to pan over the area of Montreal, Quebec, Canada. The map can be set to any area. The routing used is set to the OSM server, which is the default, and the fastest route between two points is always selected. This helps the vehicles get to chargers using the fastest route, as opposed to the shortest route which may have more traffic and may lead to a longer travel time, hence more battery consumed,

Using more elements from the aforementioned GIS library, GIS areas are defined on the map. For simplicity's sake, the first area defined is the center city of Montreal-*montreal*, within this two more areas are defined, namely the *financialDistrict*, and the *residentialArea*. More areas can be added, as needed.

Furthermore, *GISPoints* are defined, and *GISRoutes* are created between these points, to form a network where the majority of the *ElectricVehicle* traffic is to be noted.

The image below represents this, with the thick, brown dotted line as the area representing *montreal*, the green region representing the *financialDistrict*, and the brown shaded area defines the *residentialArea*. The location signs represent the GISPoints, and the small, red dotted lines represent the GISRoutes between the given GISPoints.

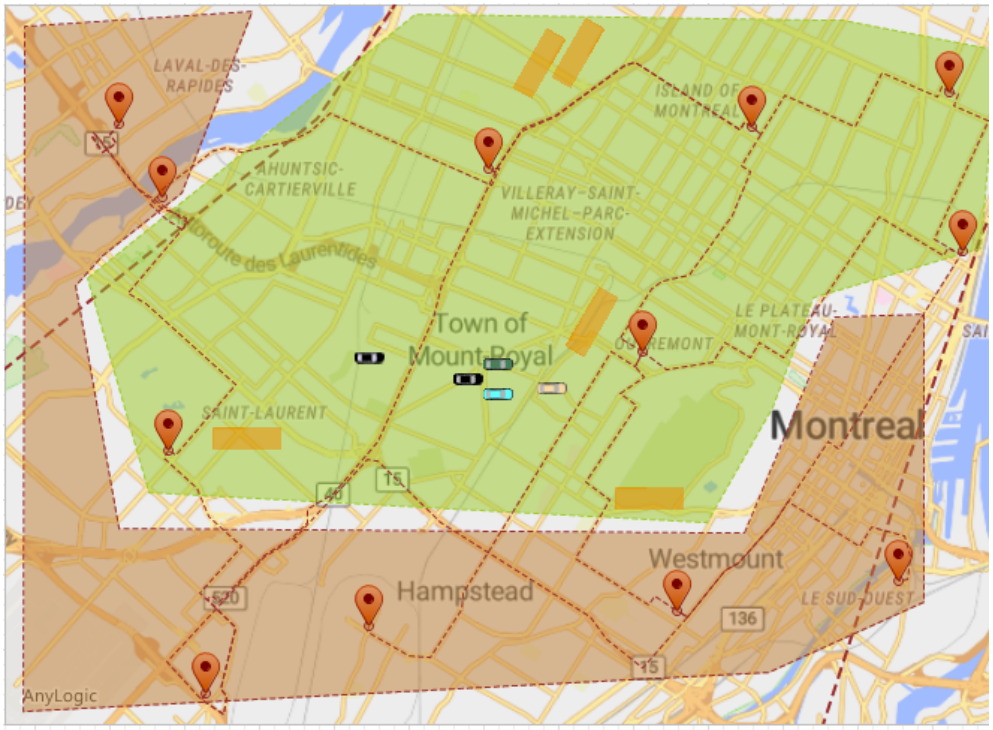

Image 2: GIS map

6.4.2 ElectricVehicle

A Java class was created by the name of *ElectricVehicle*, to serve as a superclass of all different types of electric vehicles that may be configured for this project.
The screenshot below (image 2) shows the state chart created for the *ElectricVehicle* class.

This class has its own variables and functions.

Variables

- *batteryPercentage-int*: tracks the current battery percentage of the *ElectricVehicle* object. Its default value is set as 100.
- *nearestFree-SuperCharger*: stores the nearest SuperCharger that is currently free.
- *superChargersList-ArrayList*: gets the list of SuperChargers from Main.

Functions

- *getNearestFree()*: This function gets the current coordinates of the car, and loops over the *superChargersList*, to calculate which *SuperCharger* is currently free, and also closest to the current car in question. For the sake of simplicity, the distance formula based on the Pythagorean theorem in Euclidean geometry is used.
- *updateBatteryPercentage()*: Decreases the *batteryPercentage*, every time it is called. As this is the super class, it is set as 1.
- *chargeBattery()*: updates *batteryPercentage*, as the *ElectricVehicle* charges. This is also set with a default value of 1, unless overridden in the child classes.
- *updateMoneyMade()*: updates the amount of money made by the *SuperCharger* currently in use by the *ElectricVehicle*.

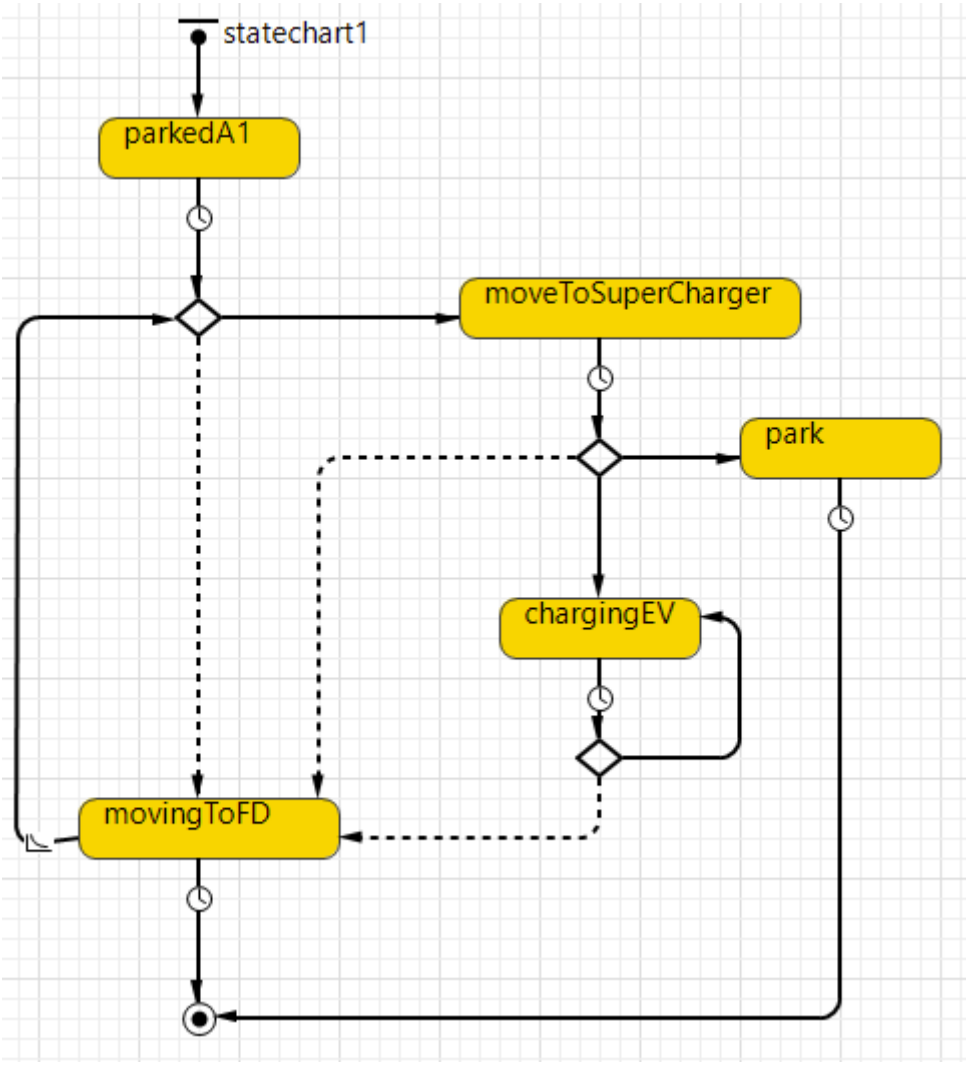

Image 3: State chart for the ElectricVehicle class.

The state chart above follows the following logic:

1. On entry in to the state chart, that is when an object of this type is created, the first state is *parkedA1*, which states that a car is created at a random within the area defined as the *residentialArea*.
2. Once it exits this state, it makes a decision to check if the *batteryPercentage* has dropped to below 40%, then it looks for a *SuperCharger*, and moves to the closest one that is still free.
    a. If it is able to find one, the car will move to it, and start charging. This will result in an increase in the *batteryPercentage*, at a fixed rate that is set using Java code in the Advanced section.
        i. The *ElectricVehicle* will continue charging until the *batteryPercentage* is a full 100%.
    b. Otherwise if the *batteryPercentage* is below 10%, and the car has been unsuccessful in finding a free *SuperCharger*, it will find a place to park itself.
3. If the car has enough charge, it will continue on it's way to the financial district, with the *batteryPercentage* decreasing at every turn through the loop.

4. When it exits the if, conditional statement, the transition moving back to the state, *movingToFD*, sets the variable *full* of the given *SuperCharger*, as false, thus available to use by another *ElectricVehicle*.

This logic is looped over, to ensure that the *batteryPercentage* is constantly kept in check.

A time series plot, from the Analysis palette is added to this class, to see the real-time *batteryPercentage* updates as the *ElectricVehicle* moves and battery is discharged, or as the car is charged and *BatteryPercentage* increases. The id of which object can be set at run-time, by accessing the class.

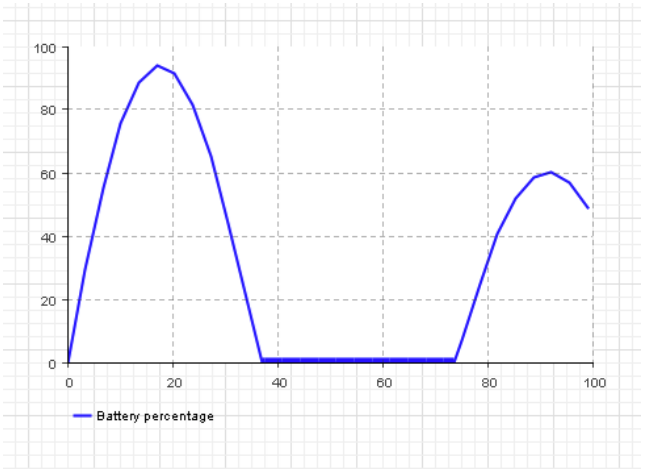

Image 4: Time plot to track batteryPercentage against model time, at run-time.

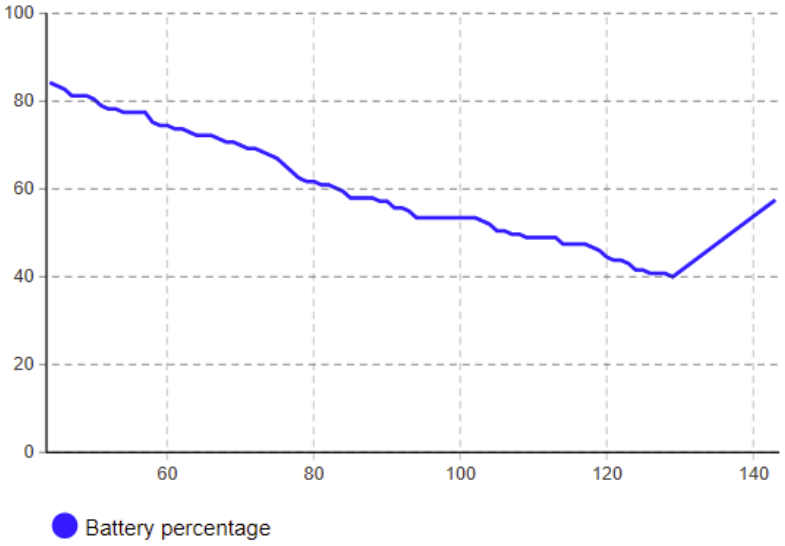

Image 5: Updates the the above time-plot in real-time, as the ElectricVehicle moves through the simulation.

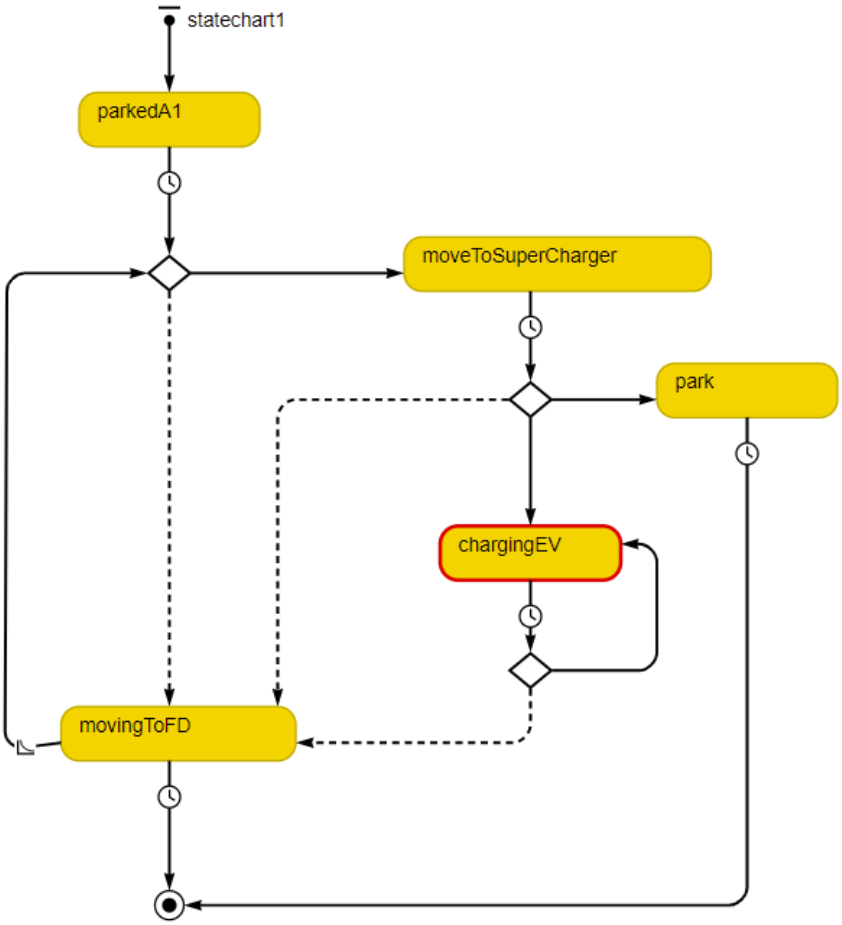

Image 6: As the batteryPercentage in the above time series plot seems to be increasing, the electric vehicle can be seen in a charging state simultaneously.

When creating the agent class, an animation can to be selected, or alternatively it can be added later too. A 3D animation of a car object was picked for this class, and will extend to all classes that inherit this class, though it can be updated or changed later.
An initial speed can also be set, and it is set at 12m/s which is roughly 43.2km/h. This is by taking into account the traffic and slow movement of in-city cars. However, accounting for the faster acceleration than *GasCars*, it is set at this value, as the speed for *GasCars* is set at 10m/s, 36km/h.

6.4.3 Types of ElectricVehicles

EV1, *EV2*, and *EV3*, extends the *ElectricVehicle* class, as seen below.

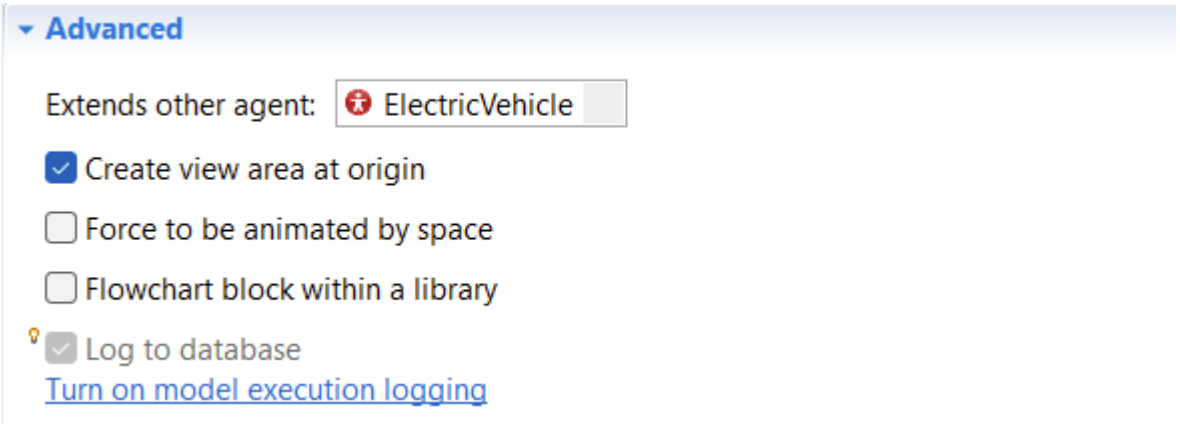

Image 7: Setting EV1, EV2, and EV3 to extend the functionality of ElectricVehicle as its super class.

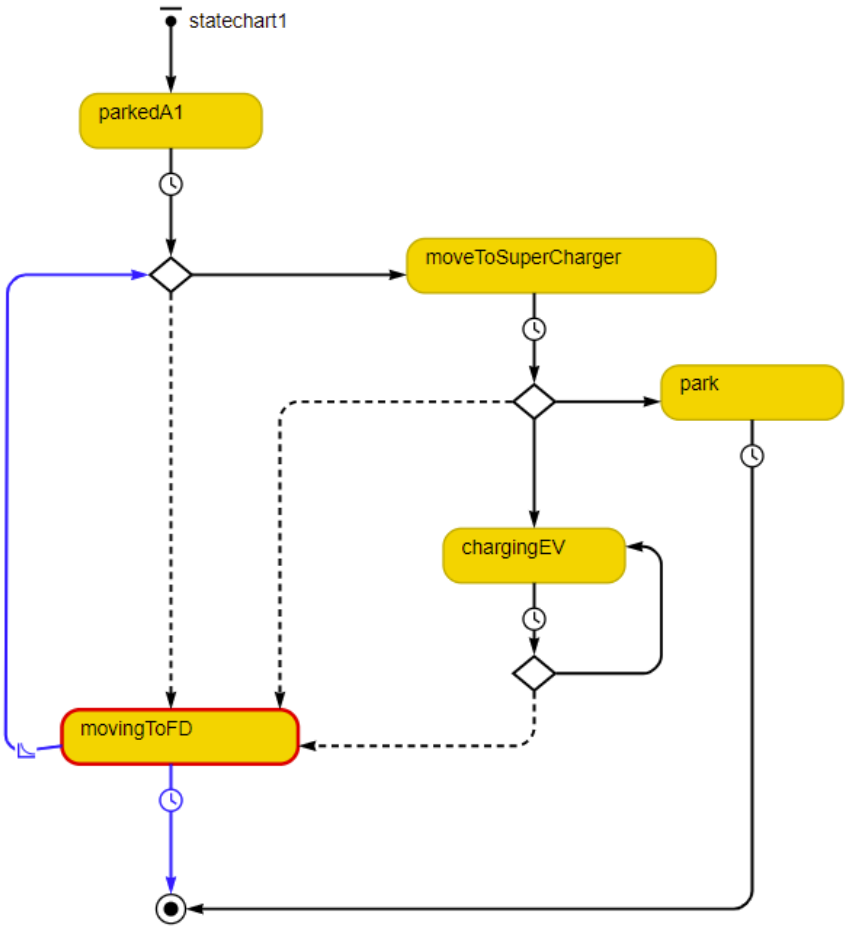

Image 8: Current state that an ElectricVehicle is in, is highlighted.

Two functions from the superclass, *ElectricVehicle* are overridden for all new types (*EV1, EV2, EV3* for this project) of electric vehicles, that extend it.

In the future, if the project is extended to include plug-in hybrid electric vehicles or any other types of electric vehicles, the same state chart and functions can be used, and overridden on the same model as this.
No new functions are created.

When any of these are added to the *Main* class, a population of agents is created.

6.4.3.1 EV1

EV1 has a green colour and is represented by a green car on the map, during the simulation. The initial speed is maintained at 12m/s (43.2km/h).

Overridden functions:

- *updateBatteryPercentage()*: *batteryPercentage* is decreased at a rate of 0.75.
- *chargerBattery()*: *batteryPercentage* is increased at a rate of 1.25.

6.4.3.2 EV2

EV2 has a black colour and is represented by a green car on the map, during the simulation. The initial speed is set at 10m/s (36km/h).

This type of electric vehicle stuck to the default, and no functions needed to be overridden, as *batteryPercentage* increased at a rate of 1, and decreased at a rate of 1.

6.3.3.3 EV3

EV3 has a cyan colour and is represented by a green car on the map, during the simulation. The initial speed is set at 11m/s (39.6km/h).

Overridden functions:

- *updateBatteryPercentage()*: *batteryPercentage* is decreased at a rate of 0.9.
- *chargerBattery()*: *batteryPercentage* is increased at a rate of 1.05.

6.4.4 SuperCharger

A *SuperCharger* class is created.

The state chart for the *SuperCharger* is below.

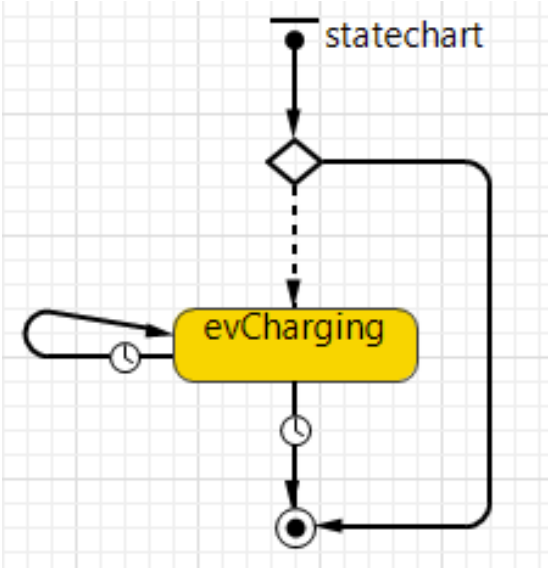

Image 9: State chart for the SuperCharger

An object of this type, can only be in one state, that is *evCharging*. Once it is in this state, the *SuperCharger* is set as full. Meanwhile, it can loop over this state, until the *ElectricVehicle* is fully charged to 100%.

Once an *ElectricVehicle* is done charging, it again sets the value of *full* of the given *SuperCharger* as false, therefore available to use by another *ElectricVehicle* looking for a *SuperCharger*.

Variables

- *moneyMade-double*: This variable tracks the amount of money a given object (agent) of this type has made to a given point in the simulation. The default value is 0.
    - It is noted that it takes approximately fifteen minutes for an electric vehicle to fast charge with the use of a supercharger, for a mean value of $15.
    - This brings the per-minute rate to:
        - 22/15 = 1.46667
    - This is rounded to a value of $1.5 per unit of model time in minutes.
    - This value is updated by the *ElectricVehicle* utilizing the charger, as mentioned above in 6.3.2.
- *full-boolean*: if the SuperCharger is in use, this value will be set as true, hence preventing any other *ElectricVehicle* from using it. The default for this is false, that is, available.
- *investmentMade-double*: This variable stores the value of the investment that was made to install the *SuperCharger*. It is by default set at 12500.
    - Based on the values found online, an electric vehicle fast charger, or a supercharger per se can cost anywhere between $4000 to $7000.
    - Installation can cost another $1000 to $2000,
    - This plus location rental and maintenance can add up, and a mid-value of $12500 was set as the *investmentMade*.
    - In future iterations, this can be set as editable by users through the graphical user interface of the simulation itself. This is made easier by storing this value as a variable.

Each *SuperCharger* agent is created individually, rather than a population of agents. They are all stored inside an *ArrayList* in the *Main* class. *SuperChargers* are represented as small, orange rectangles on the GISMap, on which *ElectricVehicles* park themselves when needing a charge, i.e. with a *batteryPercentage* below 40%.

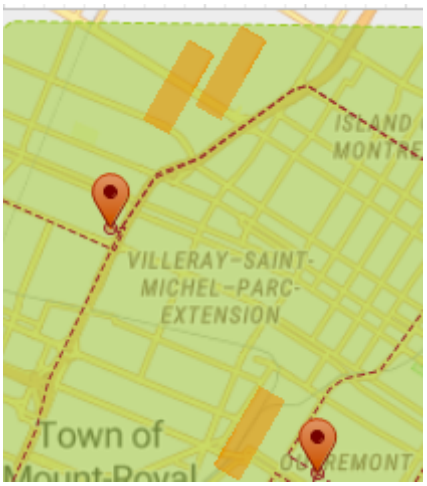

Image 10: SuperChargers represented on the GISMap.

As part of this class, a time-series plot is also added that tracks the amount of money earned, or *moneyMade* by the given agent against a unit of model time in model time minutes.

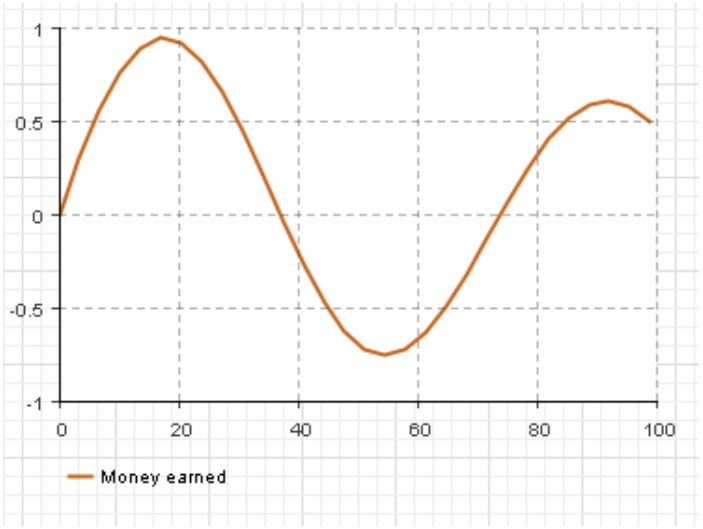

Image 11: The money earned by the given supercharger.

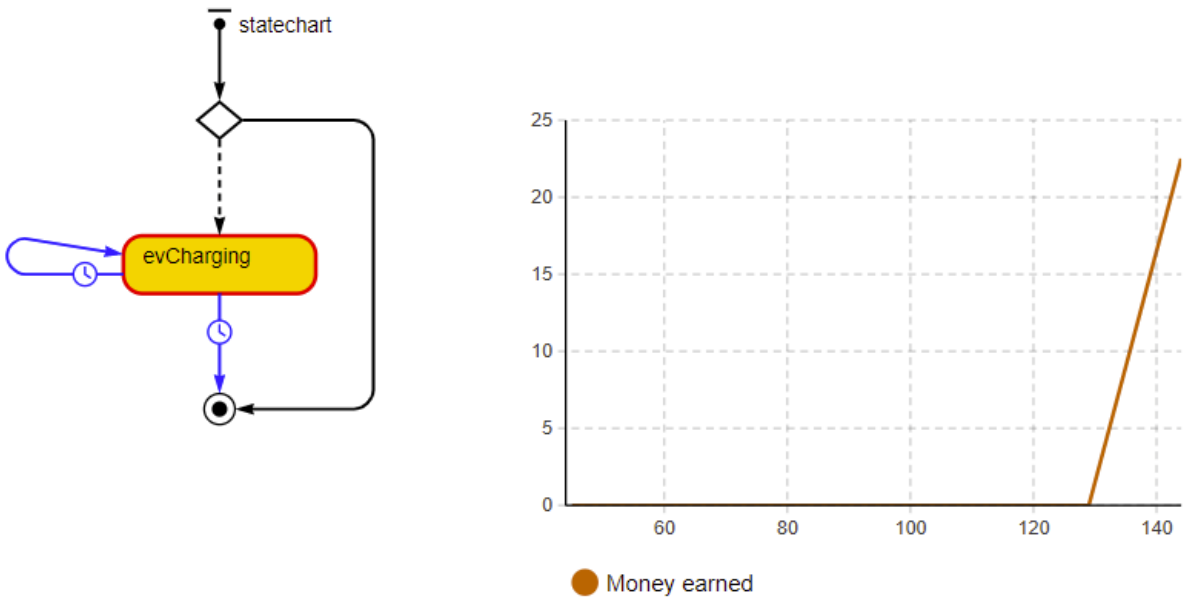

Image 12: Screenshot from the simulation at run-time as the money earned by a supercharger increases. It is also seen that the given SuperCharger is in the evCharging state, and the money earned increases at a constant rate, i.e. linearly.

6.4.5 GasCar

To accurately emulate a real-world scenario, there was a need for gas cars on the road. This would help properly simulate road traffic in the city, hence how the electric vehicles will travel along roads, impacting their battery consumption and by relation, the *batteryPercentage* too.

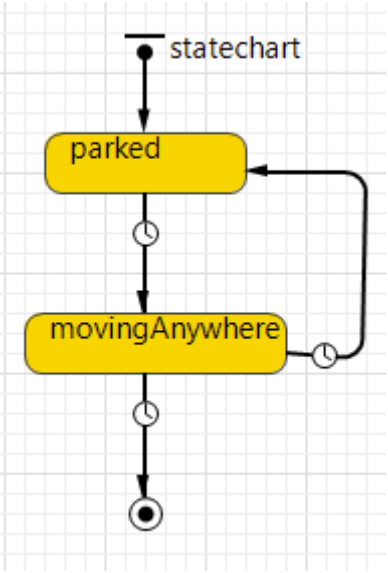

Image 13: GasCar state chart.

As can be seen in Image 12, above, a *GasCar* can be in one of two states, that is *parked*, or *movingAnywhere*. *GasCars* can move on any road, not necessarily defined by the *GISNetwork*.

The *parked* state creates a random point, within the City of Montreal, and then moves to the next state, which is *movingAnywhere*. The agent will loop between these two states, in a bid to keep them moving and maintain traffic on the roads.

As seen in Image 13 below, the amount of *GasCars* on the road helps to simulate traffic on the roads properly.

GasCars are seen in the cream-white colour, so as to not be distracting to the eye, and by contrast, *ElectricVehicles* have sharp, dark colours.

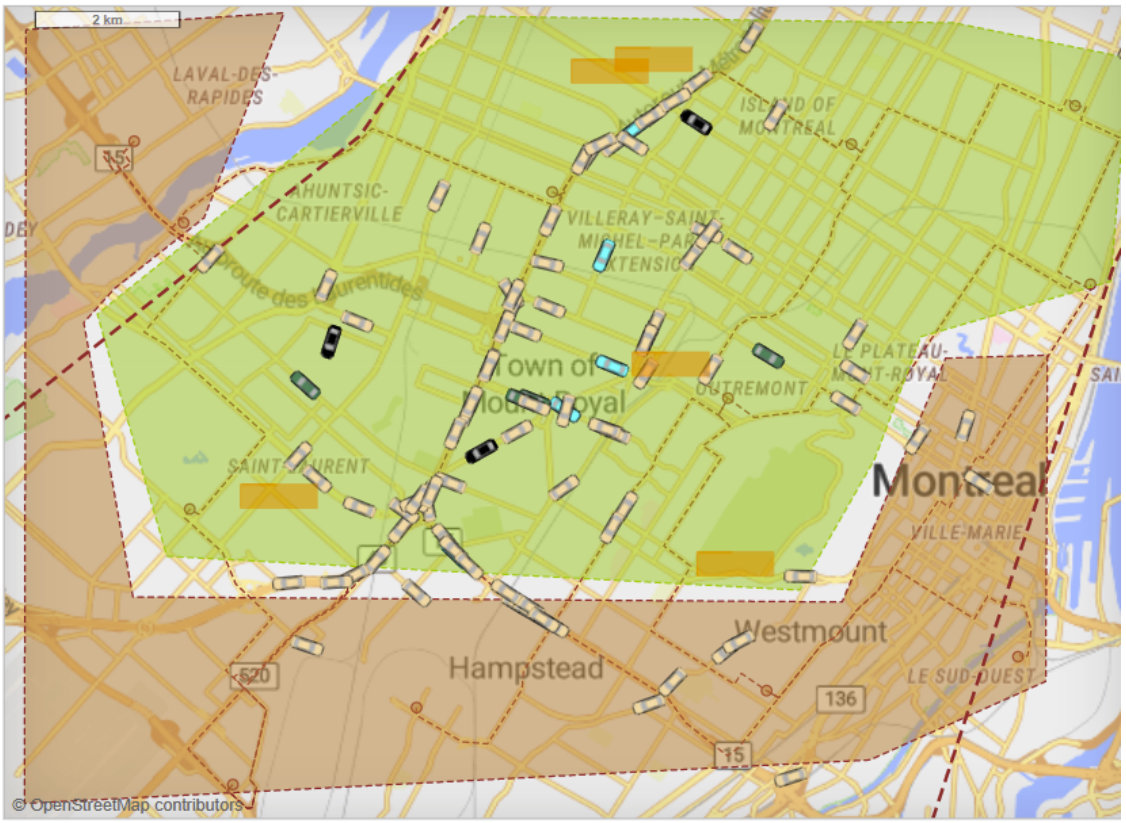

Image 14: Run-time image of GasCars, EV1, EV2, and EV3s on the road emulating traffic in the City of Montreal.

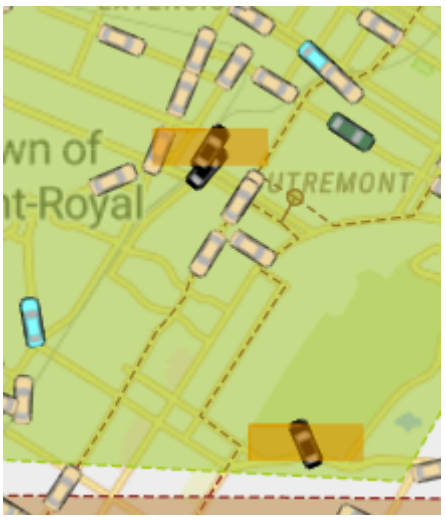

Image 15: ElectricVehicles parked at SuperChargers.

6.5 Main Class

6.5.1 Agent creation

Based on figured reported by 'The Gazette', as of April 2023 montreal had a 12% population of electric vehicles, up from 0.7% in 2015. (Mahoney et al., 2023) If taken linearly this is a 150% increase every year, for the past eight years.

Emulating this, populations of vehicles were created:

- *EV1s*: initial population of four.
- *EV2s*: initial population of three.
- *EV3s*: initial population of five.
- *GasCars*: an initial population of eighty-eight was created.

This brings it to a total of a hundred vehicles on the road, of which twelve are *ElectricVehicles*, therefore matching the current electric-to-gas vehicle ratio on the roads of Montreal.

To begin with, five individual *SuperChargers* are created, and placed along the *GISNetwork*, as these are the routes along which *ElectricVehicles* mostly travel.

An *ArrayList*, *fdSuperChargers* is created, that contains all the *SuperCharger* objects to keep track of them. As mentioned above, these objects are passed to the *ElectricVehicle* agent class, which loops over the objects in this *ArrayList* to find the closest charger that is not full to a given *ElectricVehicle*.

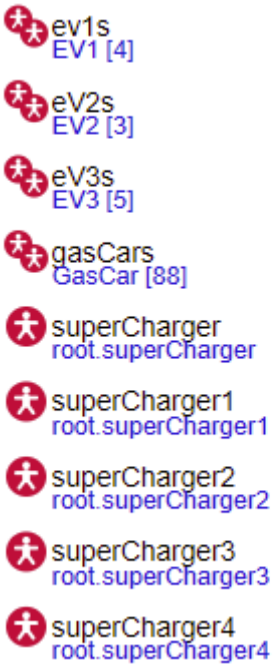

Image 16: The agent classes and number of agents of each type in the population are seen in the brackets in blue text.

6.5.2 Variables and Functions

The *Main* class also needs to keep track of certain values for analysis and computation at run-time.

Variables

- *evCount-int*: This variable keeps track of the total number of *ElectricVehicles* on the road.
- *gasCarCount-int*: This variable keeps track of the total number of *GasCars* on the road.
- *moneyMade-double*: Stores and tracks the total amount of *moneyEarned* by all the *SuperChargers*. Dynamically updates at run-time.
- *totalInvestment-double*: Stores the total amount of investment required to purchase, install and maintain all the SuperChargers placed in the city.
- *carsLookingForChargers-int*: Keeps track of the number of *ElectricVehicles* that have a *batteryPercentage* below 40%, and are looking for a charger, but are not able to find one, owing to them being full. This indicates the need for more SuperChargers.
- *freeChargers-int*: Keeps track of all the SuperChargers that are not full, i.e. available to use, thus free.
- *carsNotCharged-int*: This variable tracks the number of *ElectricVehicles* that ended up having to park themselves, because of the *batteryPercentage* dropping to below 10%, without being able to find an available SuperCharger to charge itself.
- *fdSuperChargers-ArrayList*: Stores all the *SuperCharger* objects.

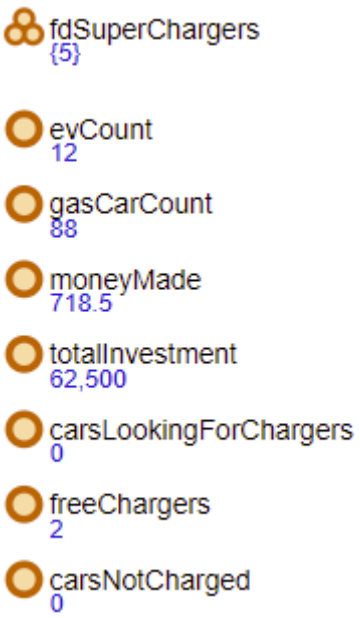

Image 17: The variables are seen at run-time, with their current values written below them in blue.

Functions

The list of functions in the *Main* class are given below, along with some snippets of code showing the main functionality of the methods given.

- *int calcCarsNeedingCharge()*: calculates the number of cars currently looking for a SuperCharger.
    - `carsLookingForChargers = count(ev1s, p -> p.batteryPercentage < 40) + count(eV2s, p -> p.batteryPercentage < 40) + count(eV3s, p -> p.batteryPercentage < 40);`
- *double investmentMade()*: Calculates the total amount of investment made, to install all the SuperChargers.
    - ```
      for (int i=0; i<fdSuperChargers.size(); i++) {
          investment += fdSuperChargers.get(i).investmentMade;
      }
      ```
- *double calculateMoneyEarned()*: Calculates the total amount of moneyEarned by all the SuperCharger agents.
    - ```
      for (int i = 0; i < fdSuperChargers.size(); i++) {
          moneyMade = total + fdSuperChargers.get(i).moneyMade;
          total = moneyMade;
      }
      ```
- *double roiCalculator()*: Calculates the return on investment earned, and later on uses this to estimate the approximate time it would take to get that return on investment.
    - `((moneyMade/totalInvestment)*100);`
- *String createText()*: Creates and returns a String that contains general information about the model at run-time.

- *String statsText()*: Creates and returns a String object that contains model statistics.

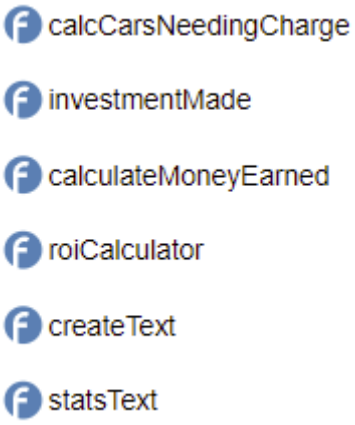

Image 18: The functions seen at run-time. It is good-practice to show the functions in the main model area.

6.5.3 Events

AnyLogic uses events to schedule tasks at run-time. These can be model delays or timeouts.
This model uses two events to dynamically update the model and data during run-time.

Event-cyclic: This event runs cyclically every few minutes in model time, to update the text and statistics texts by calling the *createText()* and *statsText()* functions. The Strings returned are used to update the text inside the text objects placed in this class. These are updated as the model runs and are shown to the user.
calcInvestment: This event runs once, when the model starts, to calculate the total amount of investment made using the *investmentMade()* function.

6.5.4 Dynamic model-change traffic at run-time

AnyLogic has the capability to allow user interaction with models, as well as dynamic updates at run-time.
To showcase this and the impact of adding more traffic on the roads, the model contains the option to add more vehicles of any given type. These vehicles show up on the map, in run-time and portray the expected functionality.

Clicking the ‘Add more EV’s’ button adds, three new *ElectricVehicles*, one of each type: *EV1, EV2, EV3*. The relevant variable is updated accordingly. The ‘Add more Gas Cars’ button adds twenty more gas cars, and updates the variable keeping track. This ratio helps maintain the current status-quo of more gas cars to electric vehicles. However, the user has the option to only add more ElectricVehicles and see the impact of those.

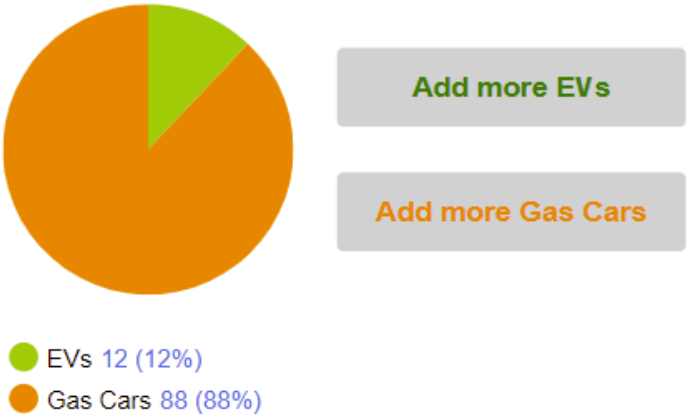

Image 19: Add more ElectricVehicles, or more GasCars. The pie chart tracks the number of each type of vehicle, as well as representing the percentage of each.

Another functionality for dynamic usage is the GISMap can be panned in or out, using the zoom in and zoom out buttons, as seen below.

Image 20: Zoom in or Zoom out of the GISMap.

6.5.5 Statistics

Section 6.4.2 of this report shows variables and functions that store, calculate, update and track the model variables, and statistics.
These are then added to two different statistic text objects, and *event* updates them at run time.
The two images below show how this looks at run-time.

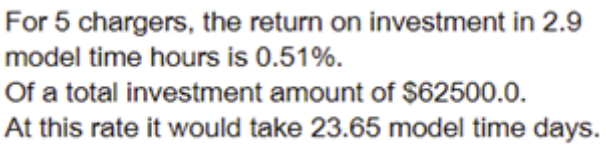

Image 21: Model run-time details

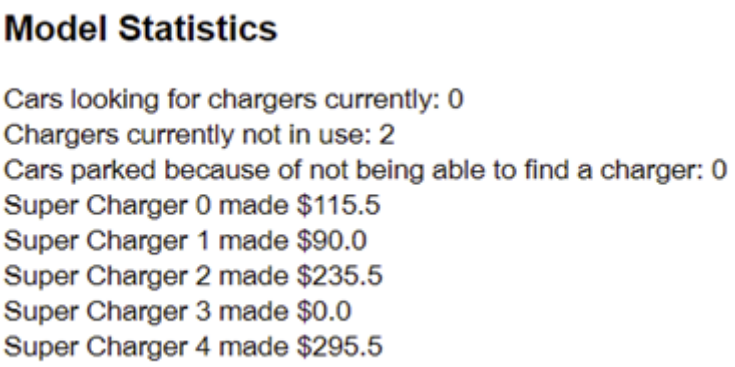

Image 22: Model statistics shown at run-time.

6.5.6 Analytics and Charts

To further visualize the statistics mentioned in this section, charts are added to the simulation that shows progress at run-time.
ElectricVehicle class shows the *batteryPercentage* of any given *ElectricVehicle*, and this is inherited by EV1, EV2, and EV3. This can be seen above in images 3 and 4.

Similarly, for SuperChargers, the *moneyMade* by each is tracked along a time-series plot, as seen in images 10 and 11.

A pie chart is used to track the number and ratios of *ElectricVehicles* to *GasCars*.

For further analysis, some more time-series plots are added to the main simulation.

1. The rate of *batteryPercentage* discharge or charge of the different types of *ElectricVehicles*. This is plotted against the model time unit.

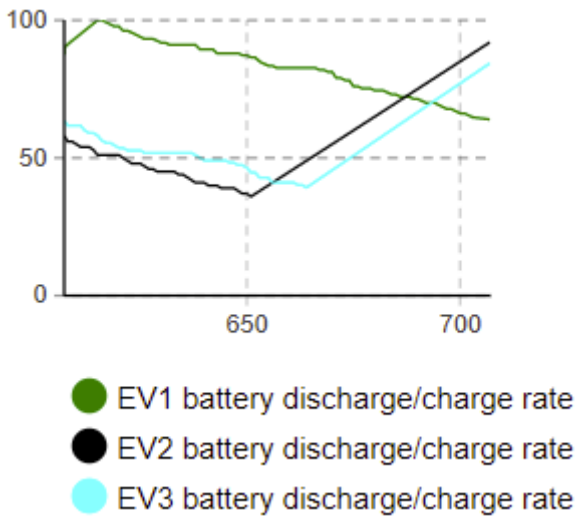

Image 23: Battery Percentage of types of EVs. The line colour is coordinated with the colour of the EV on the map.

2. The total *investmentMade* and *moneyEarned* till now, plotted against model time units. This will visualize the rate of return on investment, and the exact time at which the amount of the total initial investment is crossed.

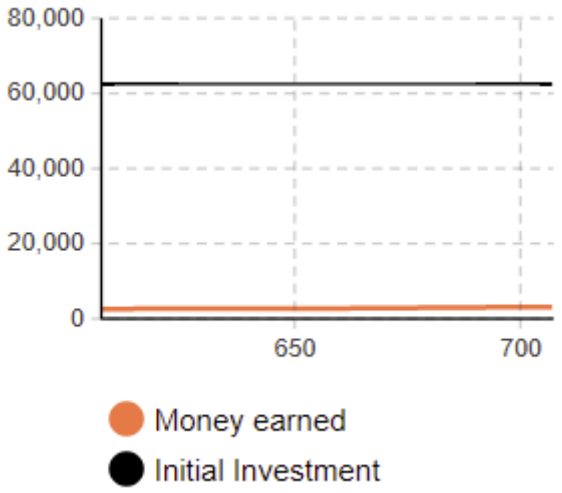

Image 24: Time-plot of money earned with time.

3. The number of cars looking for chargers, compared to the free charger available and cars which parked without finding a charger. This will help to find the optimal number of chargers.

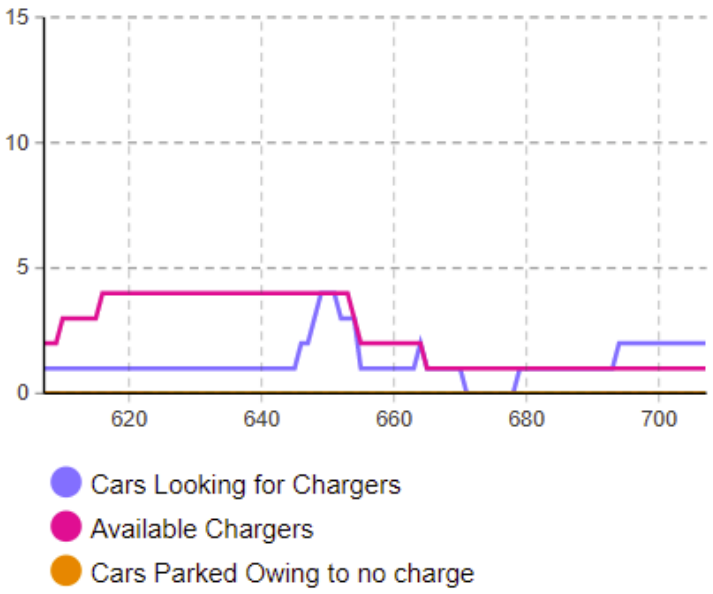

Image 25: ElectricVehicle statistics regarding charge status.

6.6 Complete Simulation

The final project simulation, with all complete elements can be seen below, in Image 25.

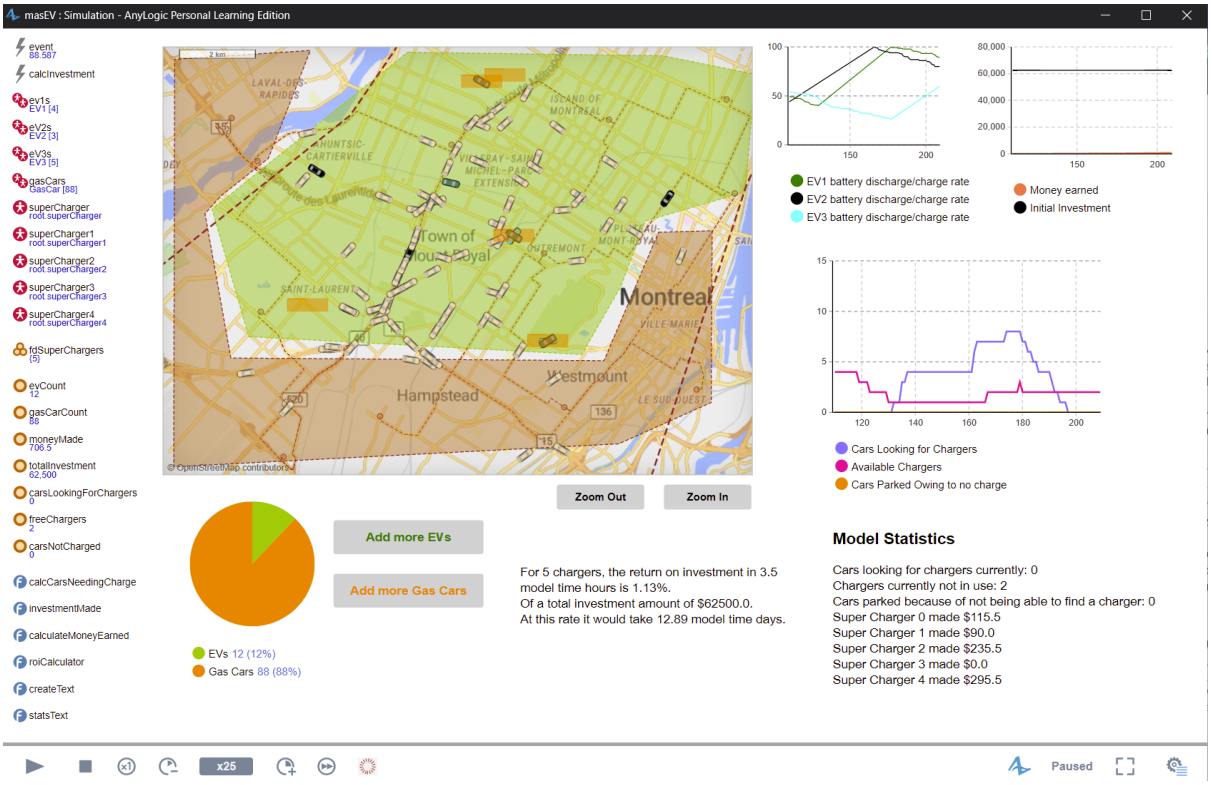

Image 26: Complete simulation model.

7. Optimizing ROI and number of stations

The objective of this simulation is to place the optimal number of superchargers in the most unneeded locations.

The adoption of electric vehicles is increasing exponentially by the year. With more government incentives and education about being green, the number of electric vehicles on the roads has increased, and the ratio of electric vehicles to gas vehicles has also grown.

7.1 Base Scenarios

The model starts off with a base scenario with twelve *ElectricVehicles* and five *SuperChargers* scattered around the area defined by the *financialDistrict*. There are eighty-eight GasCars to emulate traffic.

The total investment made is $62500 for this model, at $12500 per charger.

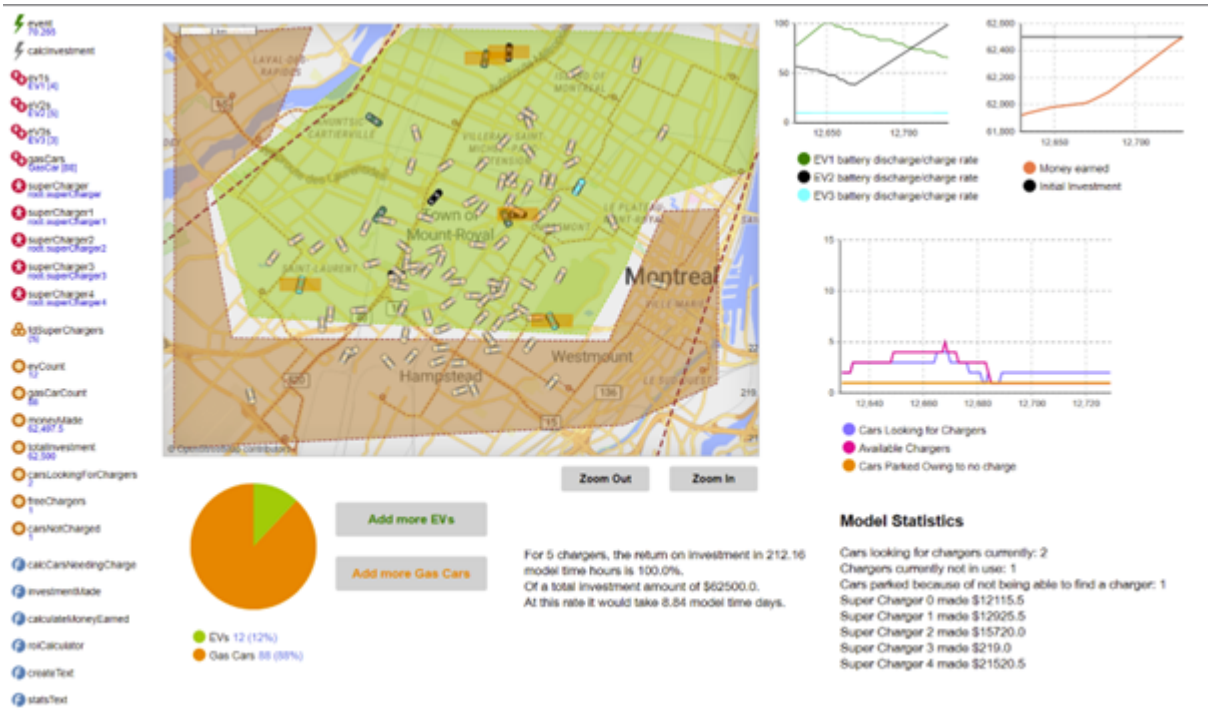

Image 27: Final state of this scenario, at 100% return-on-investment.

For 5 chargers, the return on investment in 212.16 model time hours is 100.0%.
Of a total investment amount of $62500.0.
At this rate it would take 8.84 model time days.

Model Statistics

Cars looking for chargers currently: 2
Chargers currently not in use: 1
Cars parked because of not being able to find a charger: 1
Super Charger 0 made $12115.5
Super Charger 1 made $12925.5
Super Charger 2 made $15720.0
Super Charger 3 made $219.0
Super Charger 4 made $21520.5

Image 28: Zoomed in model statistics for the base scenario.

As can be seen from images 26 and 27, a 100% return on investment is made in 212 hours in model time units. This is roughly 8.89 days.
It can be seen that superchargers 0, 1, and 2 have all made approximately the initial amount that was invested. It can be seen that supercharger number 4 has made almost twice the amount of its initial investment, on the other hand, supercharger number 3 has made barely 2% of its initial investment.

From this it can be inferred that there is a lot of traffic going along a specific road, where supercharger number 4 is located, and not enough electric vehicle traffic near supercharger number 3.

7.2 Iterative Improvement

The process of optimization is an iterative process that requires several cycles of continuous improvement.

The base scenario is taken as the control experiment run, the status quo, to be compared against.
Some constants were kept for the sake of consistency and analysis of the rate of return on investment, and the number of chargers. In optimizing the number of chargers, the location of chargers was also optimized.

- The number of *ElectricVehicles* was maintained at 12.
- The number of *GasCars* was maintained at 88, to maintain a flow of traffic on the road.
- The initial investment required to install and maintain a SuperCharger was kept at $12, 500.

The number of *SuperChargers* and placement was changed to optimize the return on investment and requirement of chargers.

7.2.1 Scenario 1

The number of *SuperChargers* was maintained, at 5 as can be seen below, but the *SuperCharger* with the least amount of money earned was moved to a more high-profile spot, with more traffic.

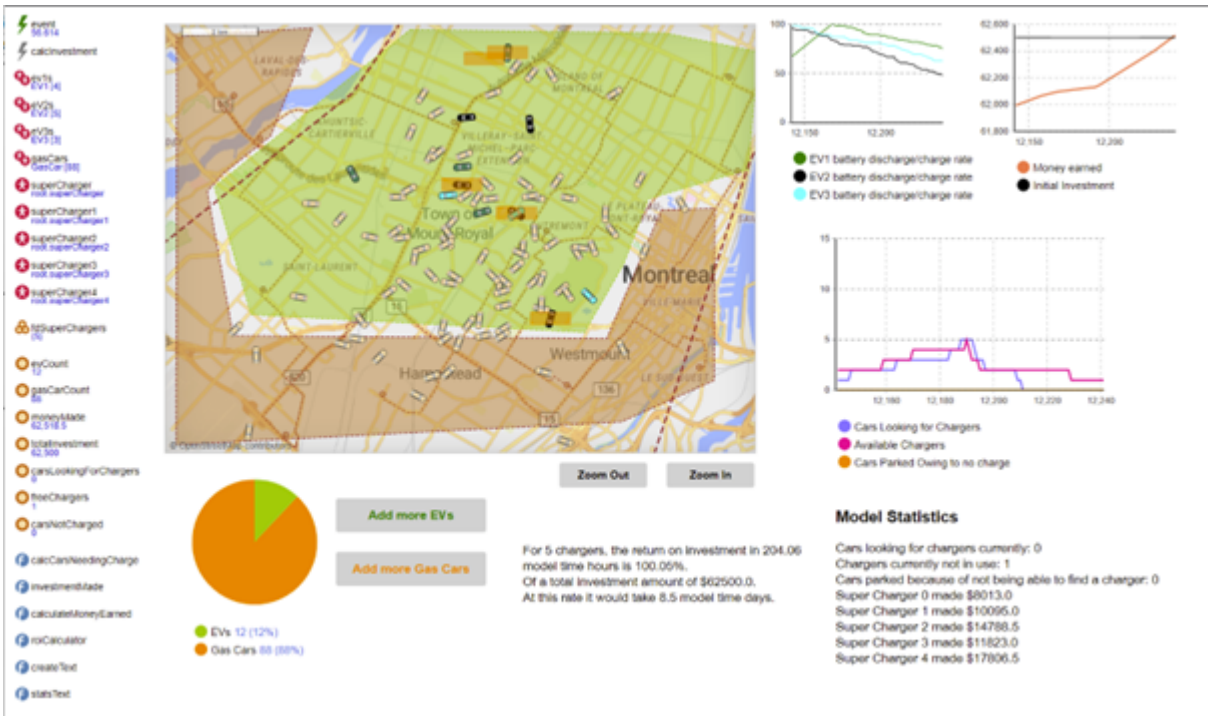

Image 29: Scenario 1, at 100% ROI.

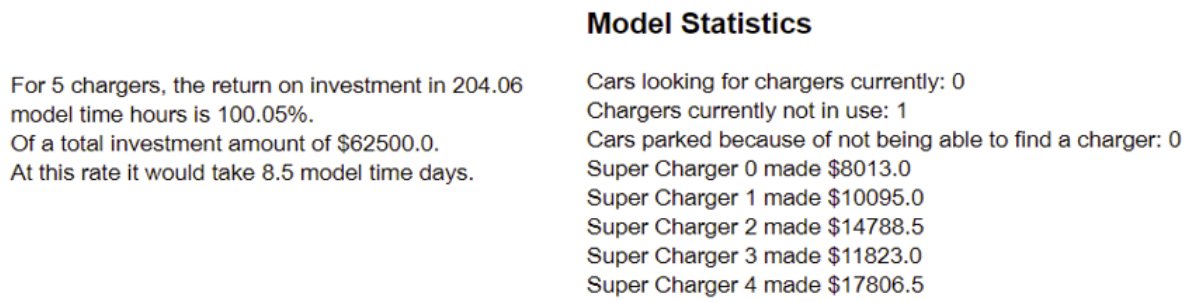

Image 30: Model statistics at 100% ROI.

The statistics above show, that while supercharger number 4 made the most amount of money, the rest of the superchargers all made a similar amount of money, and all but supercharger number 0 made approximately the amount initially invested for it.
Furthermore, it can be observed that the rate of the return on investment has increased, though not too significantly, but it is improved by eight hours which is about a 3.7% improvement.

SuperChargers 0 and 1 are located adjacent to each other, and are the two *SuperChargers* that made the least amount of money. Also it should be noted, that in the time required to get a 100% return on investment, there was no car that had to be parked owing to no chargers being available. This begs the question if five superchargers are overkill, especially with two adjacent chargers.

7.2.2 Scenario 2

For this scenario, the number of SuperChargers is reduced to four, for the given number of ElectricVehicles.

The results of this can be seen in images 30 and 31 below.

It can be noted that the values of the amount earned are definitely getting more precise, as well as more accurate, to the investment amount of $12, 500. *SuperCharger* 0 is still making the least amount of money, which can be attributed to it being slightly closer to the edge of the *financialDistrict*, compared to the rest which is much closer to the busier parts, hence with more traffic.

It takes 168 hours for four chargers to get a 100% return on investment of $50, 000, thus at this rate, it would take 210 hours to get a 100% return for $62, 500. This is a small improvement in terms of time but clarifies that reducing the number of *SuperChargers* from five to four has no detrimental impact.

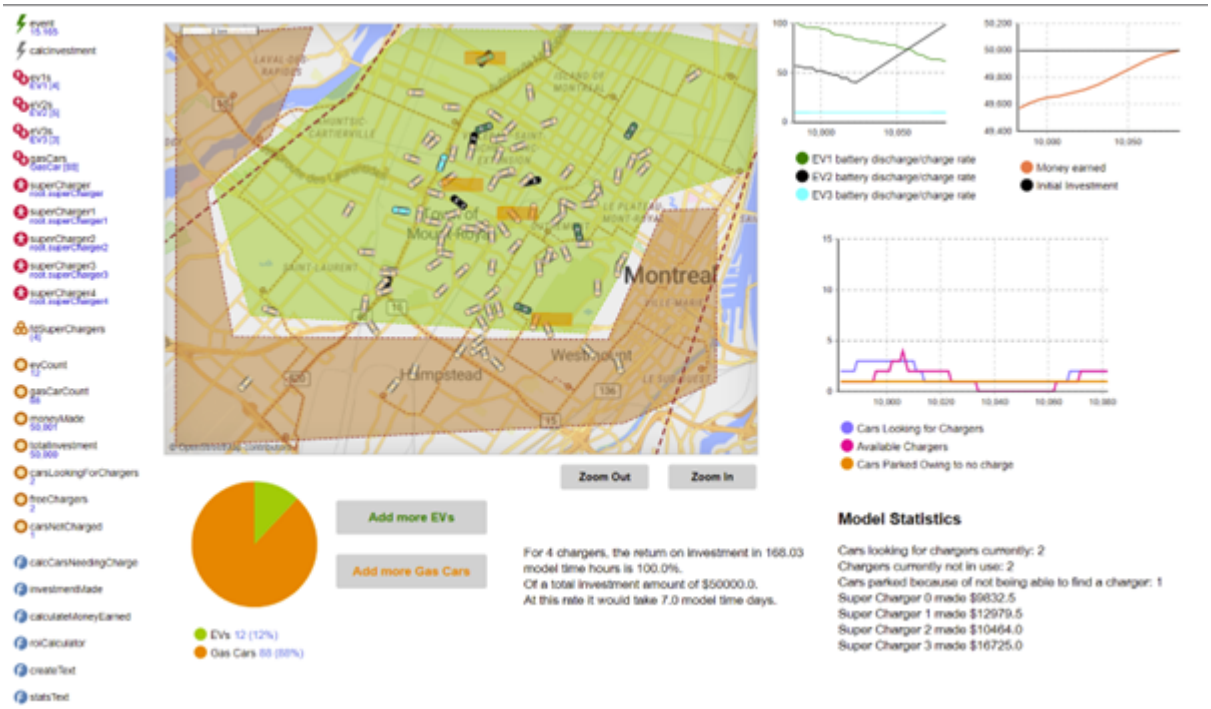

Image 31: Results of Scenario 2.

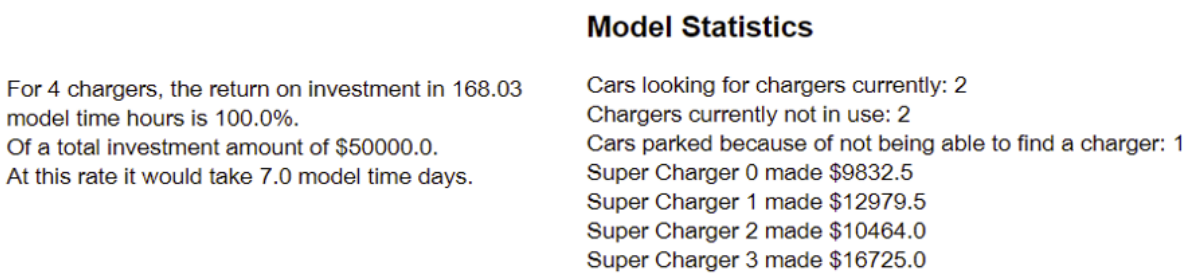

Image 32: Detailed statistics of scenario 2.

7.2.3 Scenario 3

To further test the waters, the number of *SuperChargers* was reduced to three, and results compared against the first few scenarios, and the base scenario.

The values of the amount of money earned have gotten far more precise and accurate to the initial investment value of $12, 500. It is noted that of twelve, *ElectricVehicles*, four were parked owing to no SuperChargers being available, which comes to about 33.3% of all *ElectricVehicles* on the road.

For three SuperChargers, the amount invested would be $37, 500, and it takes 183 hours in model time to get a 100% return on it, which at this rate if $62, 500 had to be returned would take 305 model time hours. This is a significant downgrade, by almost 44%.

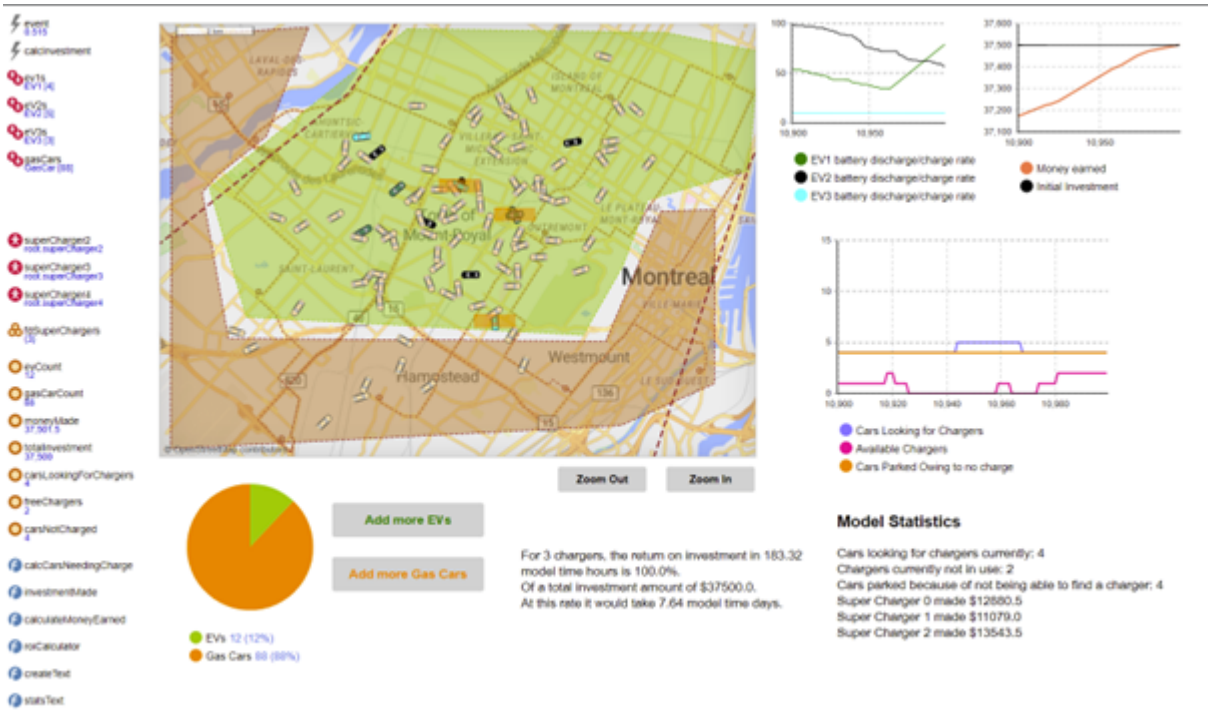

Image 33: Final results of scenario 3.

For 3 chargers, the return on investment in 183.32 model time hours is 100.0%.
Of a total investment amount of $37500.0.
At this rate it would take 7.64 model time days.

Model Statistics

Cars looking for chargers currently: 4
Chargers currently not in use: 2
Cars parked because of not being able to find a charger: 4
Super Charger 0 made $12880.5
Super Charger 1 made $11079.0
Super Charger 2 made $13543.5

Image 34: Final statistics of scenario 3.

7.3 Scenario comparison

ID	Number of EVs	Number of chargers	Time for 100% ROI (hours)	Time for 100% ROI of 62, 500 at this rate	Cars parked cause of no charger	Improvement
1	12	5	212	212	1	Control
2	12	5	204	204	0	+3.7%
3	12	4	168	210	1	+0.94%
4	12	3	183	305	4	-43.9%

Table 1: Comparison of scenarios and results.

8. Optimal solution

From Table 1, above in section 7.3, it can be noted that whilst five chargers with good placement strategies provides the best improvement, at 3.7%, it might not be the most optimal solution.
This can be attributed to the assumption we made that all *ElectricVehicles* are exclusively charged at these stations during the day, and that no *ElectricVehicle* leaves the *SuperCharger* before it is a 100% charged. These assumptions make our simulation a lot more stringent than the real-world, as cars may leave a charger before they are charged to a 100%, or travel to other parts of the city and charge there.

Since no cars ever needed to be parked because of a lack of charge, proves that the ratio of *SuperChargers* to *ElectricVehicles* of 5:12 is probably too much. Thus, scenario 3 is selected as the most optimal scenario, as it provided an improvement on the rate of return on investment, and was just enough to keep elevent out of twelve *ElectricVehicles* fully charged and running for the duration of the simulation.

9. Future Work

One of the many advantages of using AnyLogic for simulating multi-agent-based simulation scenarios is that they can be created modularly, using object-oriented practices.
This makes it very easy to scale and edit the modular solution.

Several additions can be made as the project is taken to progress further. Owing to time limitations, the scope of the project was limited, but additions can be made in the future.

- Add more types of electric vehicles to the model using real data.
- Add plug-in hybrid electric vehicles.
- Several values were assumed, as this is a proof-of-concept model, in the future real-life data can be incorporated.
- A database can be integrated with EV travel distances and battery discharge rates.
- Real data of current electric vehicle chargers can be utilized to place chargers at exactly those positions in the GISMap and optimize the solution from there.
- For now, the model starts with all ElectricVehicles *batteryPercentage* at 100%, this can be randomized so the model starts with different vehicles, to have different battery percentages.
- More types of chargers can be added, such as Type 2 chargers.
- A good feature to add in the future would be to allow the user to set the initial investment of each charger, different for superchargers and for type 2 chargers.
- Users can also be allowed to edit the price of charging the car at a type of charger per minute. This would impact the return on investment.

10. Conclusion

In summary, the proof-of-concept model conducted a thorough analysis of electric vehicle and supercharger requirements using AnyLogic, and achieved optimized placement of superchargers in close proximity to high-traffic areas without direct adjacency. This strategic placement not only enhanced the rate of return on investment. Adhering to the initial assumption of vehicles charging at only these points, and not leaving a charger until it is 100% charged produced an optimal ratio of one charger for every three vehicles. If the project may progress in the future, relaxing the initial assumptions will allow for a more realistic emulation of the real-world scenario, introducing variability to the expected number of superchargers per electric vehicle. Ultimately, the project successfully fulfilled its initial conditions and addressed the original question posed at the outset.

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Appendix

Name	Scale	Usage	Interface/ Animations	Ability to simulate socioeconomic phenomena	Computing resources required for large scale	Online resources available	Personal Preference	AI connection
AnyLogic	High Large scale	Agents as Java objects Own GUI	Very sophisticated interface to work with. Impressive **2D** and **3D** animations can be made in AnyLogic. Sophisticated **graphing**, ability to copy graphs for reporting purposes. Easy to use, better animations.	Social sciences, Economics, and Urban dynamics. **Only one to be able to combine SD with MAS.**	Closed source, free version available Works on the cloud	Vast reserve, AnyLogic help website, YouTube videos and other courses	Seems like a well-rounded system with AI integration capabilities to the model. Can utilize any external data files like Excel, text, 3D objects, CAD drawings and Java class files. Can only write snippets of Java code.	Supervised learning models can be used as functions. Reinforcement learning libraries can be integrated.
MASS (Multi-agent simulation suite)	High Large scale	Agents as Java objects Models library or FABLES own GUI	—	General purpose distributed simulations (complex socio-economic)	Free-version available	—	Can’t find the tool or any information. Seems like a good tool which could have AI integration but the link in the original report no longer exists, and can’t find information on it otherwise.	—
MATSim	Extreme	Agents as Java	—	Transport	Open-source/GPL,	—	Doesn’t seem like the	—

(multi-agent transport simulation toolkit)	-scale	objects Eclipse		mobility, GIS-based evacuation scenarios	free		best fit, similar to UrbanSim. Good for generating input demand, can be used later eg to model where to place EV charging stations, etc.	
NetLogo	Medium Large scale	Scala to JVM Any JVM-uses own programming language.	Interface available. **2D** and **3D** animations available. **Perspective** can also be changed in 3D view.	Social and natural sciences	Open-source, GPL, free	Vast reserve available online.	Limitations with respect to agent creation. Slightly smaller scale usage than AnyLogic but very close.	Can export data from NetLogo and run with AI libraries.
UrbanSIM	Large scale	Python and NumPY	—	Planning analysis	Open-source, GNU, Free	—	Doesn't seem to be the best for socio-economic simulations, better suited to urban development and transport, etc. Need to do more research.	—

Table 2: Analysis of Tools

Code

Here is a link to the following code diagrams, it is zoomable, and readable.
The link to the diagrams.net file.

Click the following button to open the file in diagrams.net, there it will be fully zoomable.

As thisproject was completed on AnyLogic Personal Learning Edition, there are certain limitations such as viewing the class code, however, the snippets of code added by me are attached as screenshots in the images below, as well as the links attached in this file.

The final project file, as well as PDF files of the following diagrams can be found on GitHub, at the following link, https://github.com/EemanJ/masev_optimization.

The video recordings of the scenarios and project description can be found at the following link: https://drive.google.com/file/d/1Chhf0A1400qCOFxB3iUmxyvtuYOeOlb-/view?usp=sharing.

ElectricVehicle Class

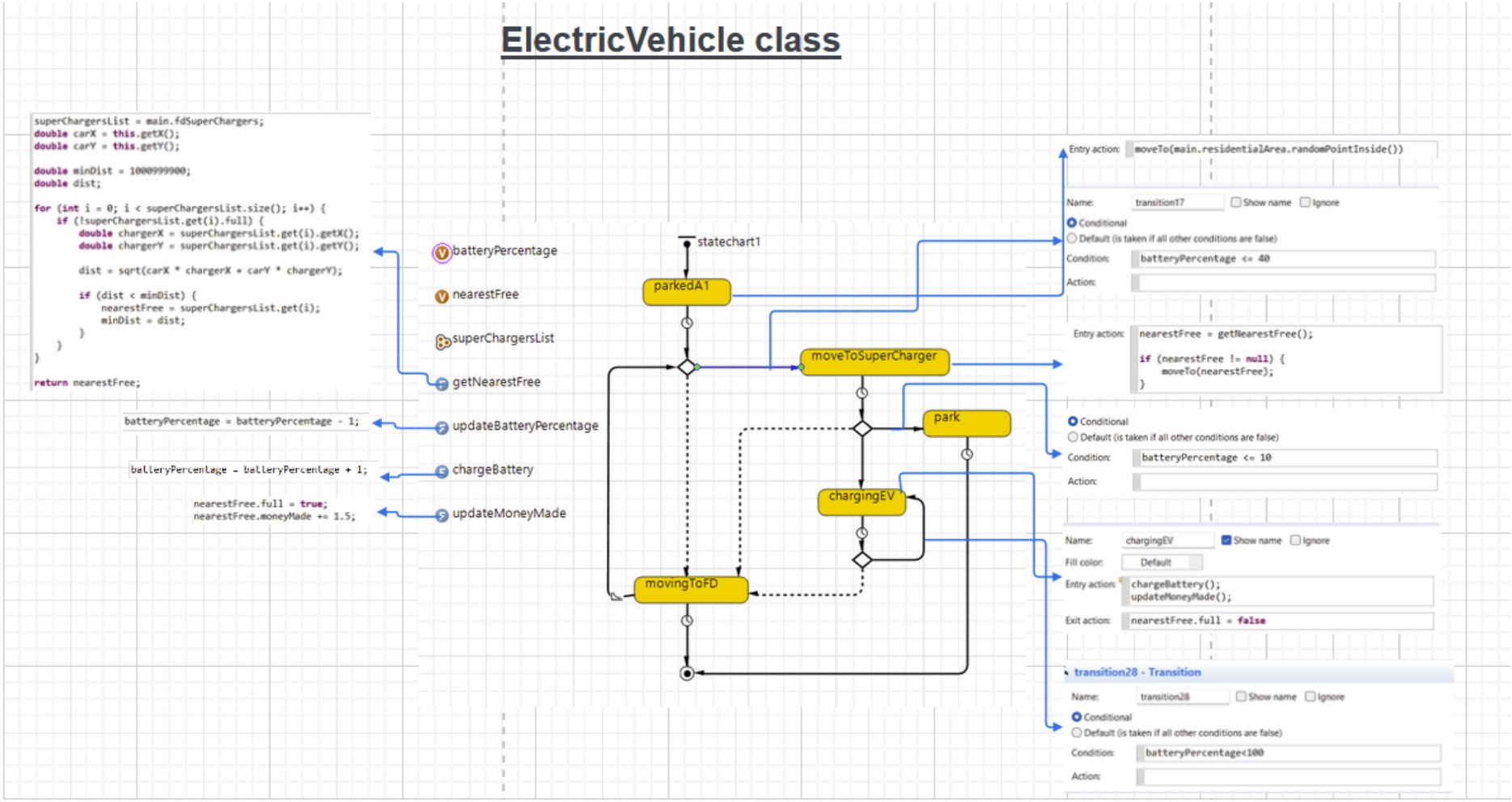

Image 0.1: ElectricVehicle class code snippets.

EV1 Class

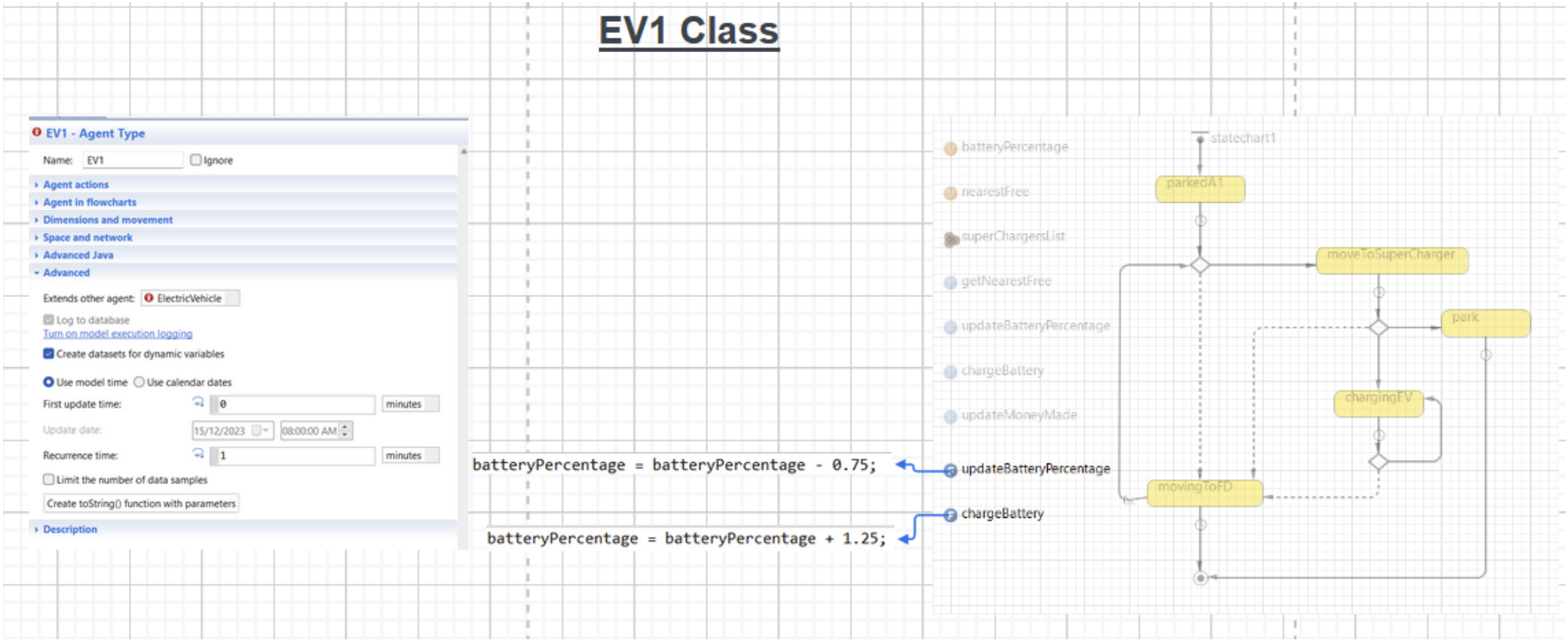

Image 0.2: EV1 class code snippets.

EV2 Class

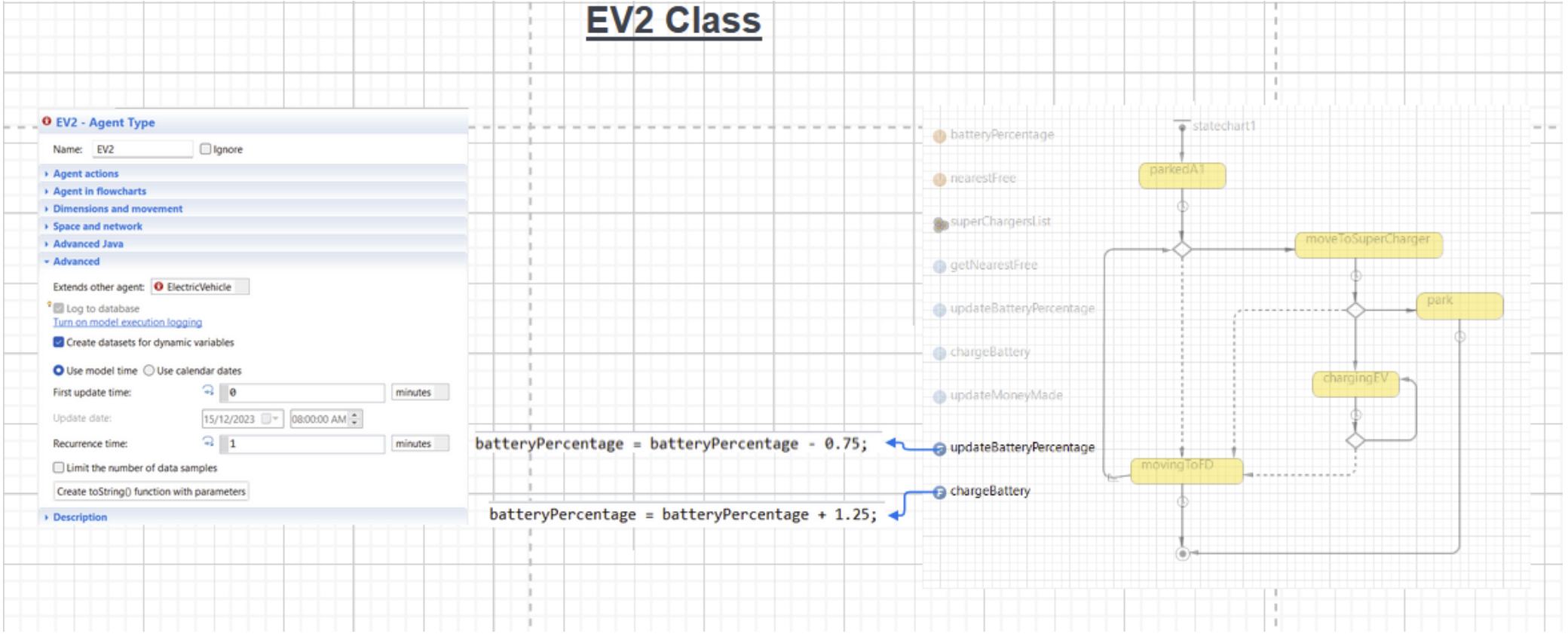

Image 0.3: EV2 class code snippets.

EV3 Class

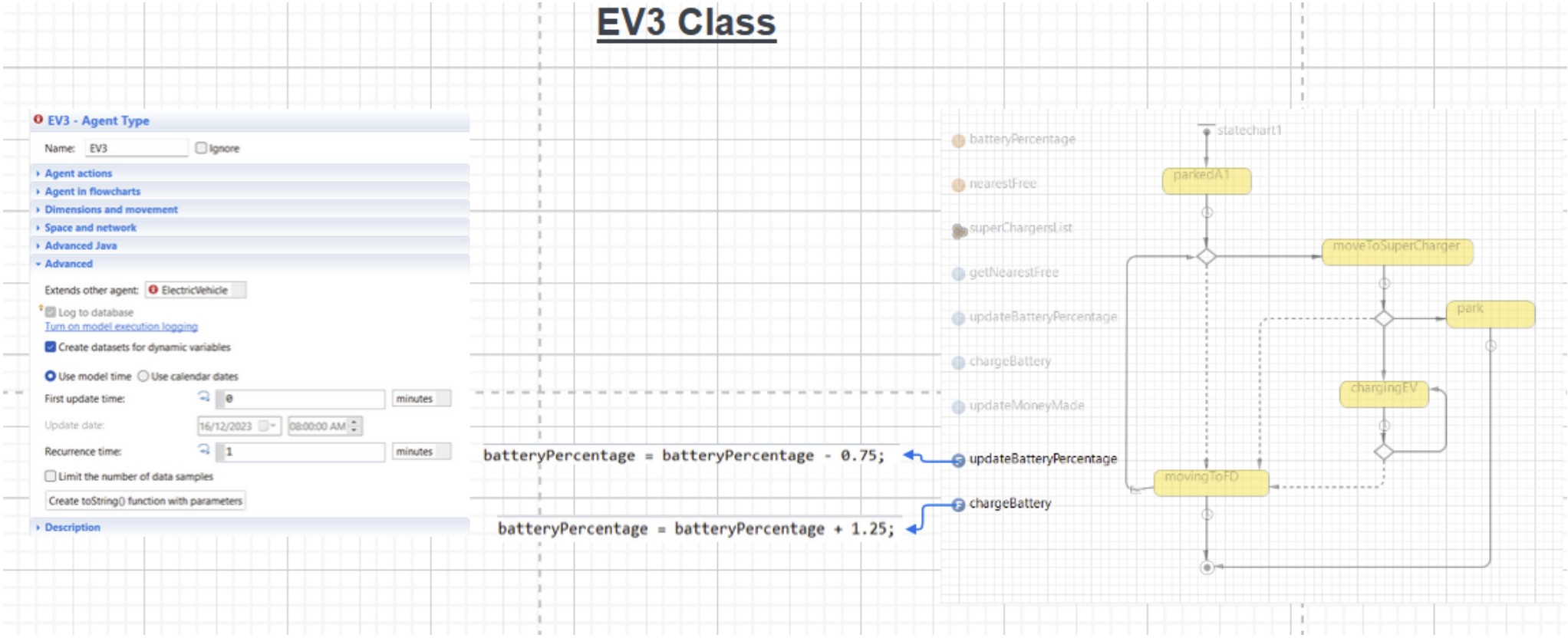

Image 0.4: EV3 class code snippets.

GasCar Class

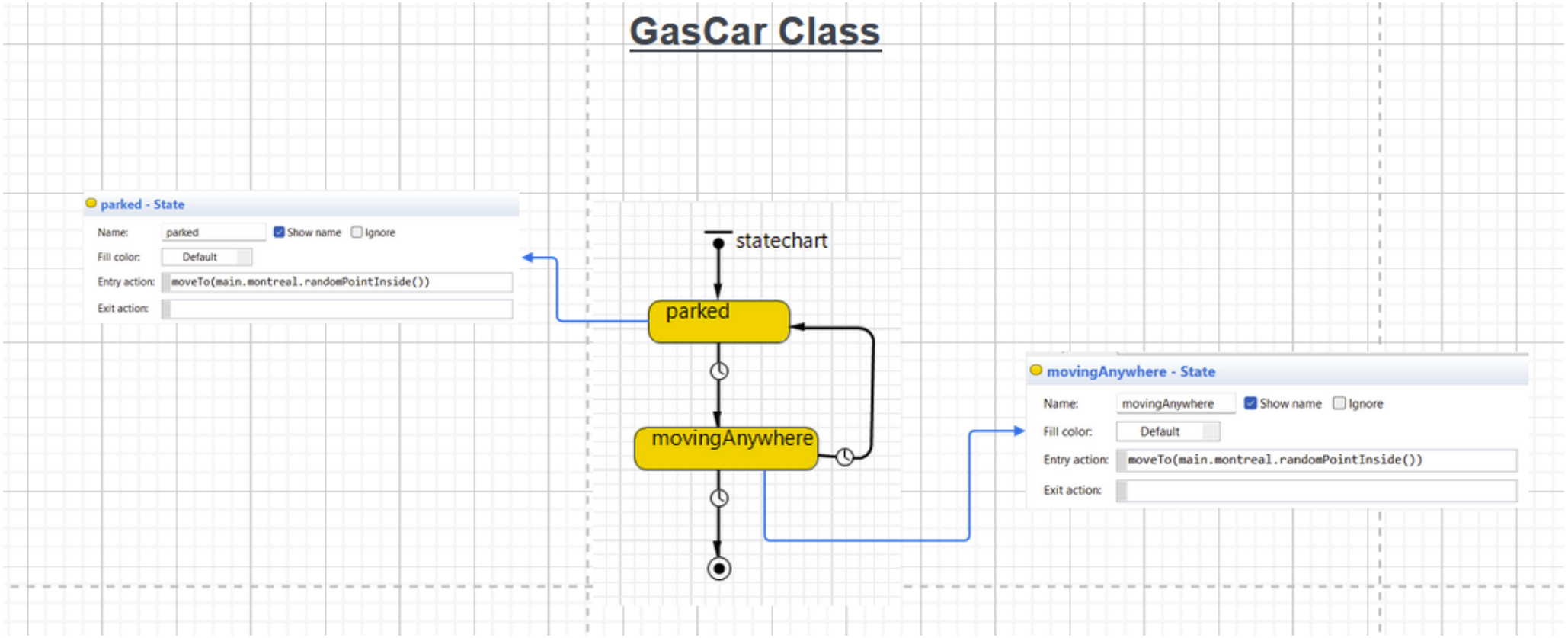

Image 0.5: GasCar class code snippets.

SuperCharger class

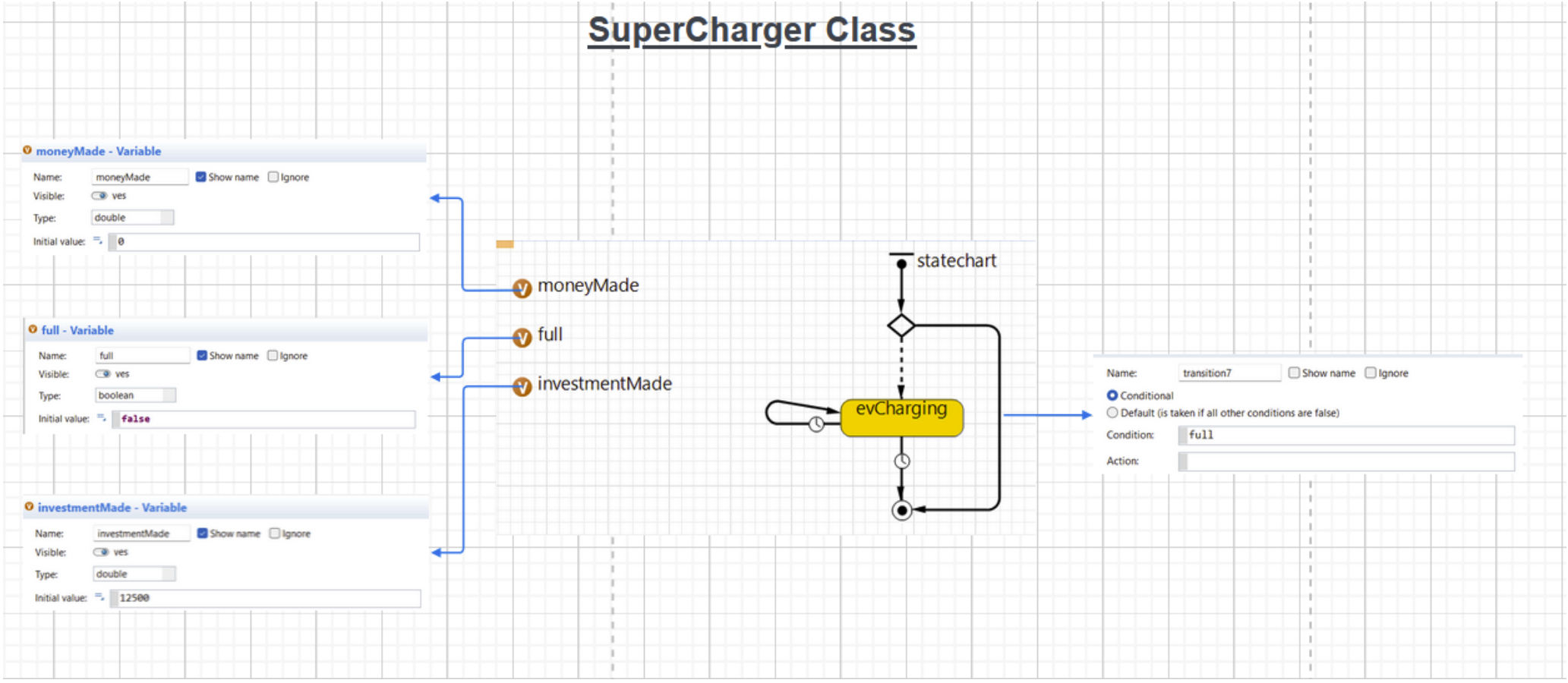

Image 0.6: SuperCharger class code snippets.

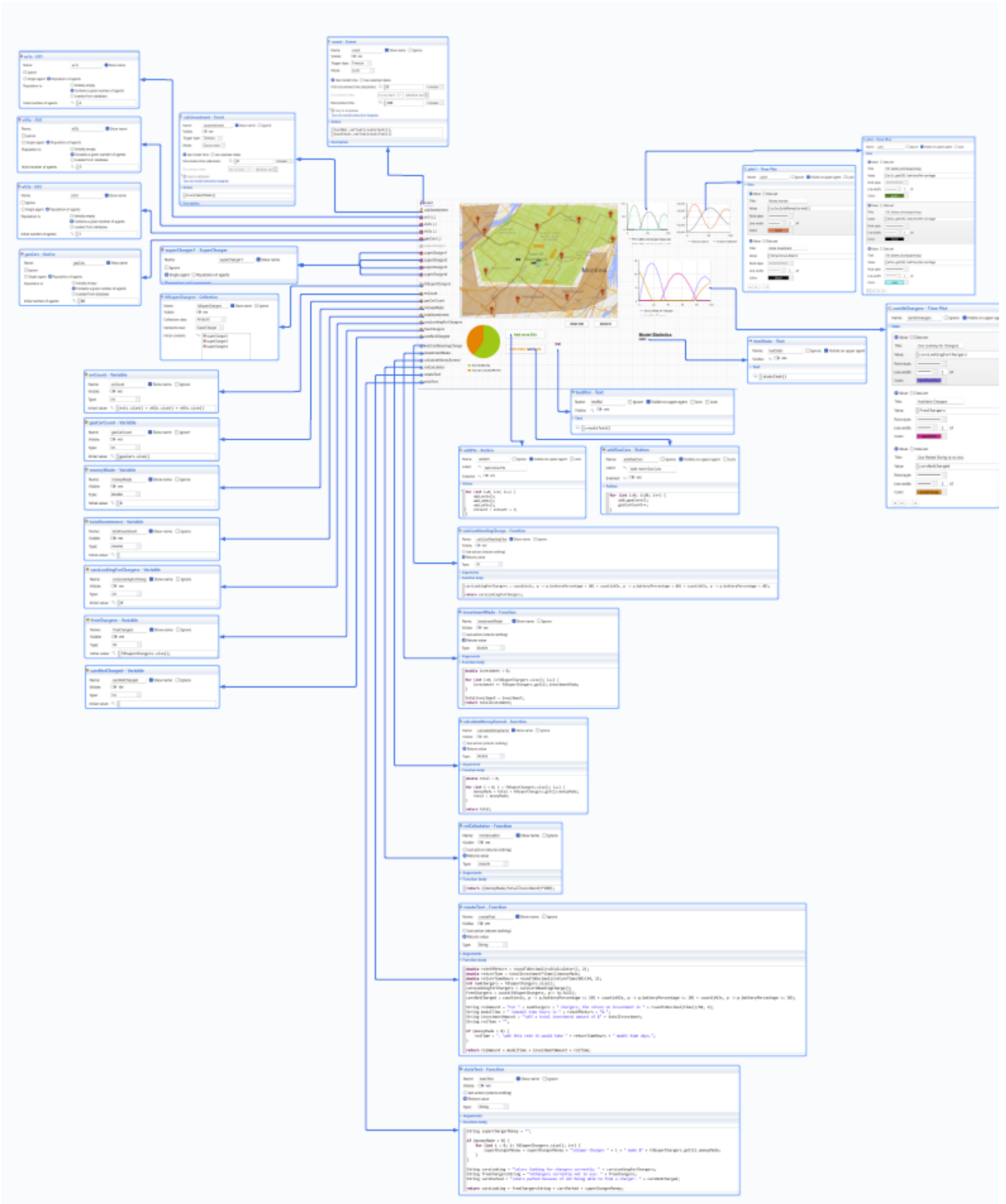

Image 0.7: Main Class code snippets. For a clearer view, open this link.

AnyLogic Project source code complete

This code can be copied in to notepad, and saved as an *.alp* file extension, e.g. *model.alp* or *masEV.alp*. When this saved file is run, it will automatically open in AnyLogic. This model requires AnyLogic 8.6.6 or greater to run.

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<?xml version="1.0" encoding="UTF-8"?>
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***********************************************
             AnyLogic Project File
***********************************************
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AlpVersion="8.8.3">
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    <Name><![CDATA[masEV-final working model new AnyLogic]]></Name>
    <EngineVersion>6</EngineVersion>
    <JavaPackageName><![CDATA[masev]]></JavaPackageName>
    <ModelTimeUnit><![CDATA[Minute]]></ModelTimeUnit>
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parameter:]]></GenericParameterLabel>
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```

```
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superCharger4 }]]></Code>
                              </CollectionInitializer>
                        </Properties>

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textStats.setText(statsText())]]></Action>
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for (int i = 0; i < fdSuperChargers.size(); i++) {
    moneyMade = total + fdSuperChargers.get(i).moneyMade;
    total = moneyMade;
}

return total;]]></Body>
                    </Function>
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for (int i=0; i<fdSuperChargers.size(); i++) {
    investment += fdSuperChargers.get(i).investmentMade;
}

totalInvestment = investment;
return totalInvestment;]]></Body>
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                        <Body><![CDATA[double rateOfReturn = roundToDecimal(roiCalculator(),
2);
double returnTime = totalInvestment*time()/moneyMade;
double returnTimeHours = roundToDecimal((returnTime/60)/24, 2);
int numChargers = fdSuperChargers.size();
carsLookingForChargers = calcCarsNeedingCharge();
freeChargers = count(fdSuperChargers, p-> !p.full);
carsNotCharged = count(ev1s, p -> p.batteryPercentage <= 10) + count(eV2s, p ->
p.batteryPercentage <= 10) + count(eV3s, p -> p.batteryPercentage <= 10);

String roiAmount = "For " + numChargers + " chargers, the return on investment in " +
roundToDecimal(time()/60, 2);
String modelTime = " \nmodel time hours is " + rateOfReturn + "%.";
String investmentAmount = "\nOf a total investment amount of $" + totalInvestment;
String roiTime = "";

if (moneyMade > 0) {
    roiTime = ". \nAt this rate it would take " + returnTimeHours + " model time days.";
}

return roiAmount + modelTime + investmentAmount + roiTime;]]></Body>
                    </Function>
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p.batteryPercentage < 40) + count(eV2s, p -> p.batteryPercentage < 40) + count(eV3s, p ->
p.batteryPercentage < 40);

return carsLookingForChargers;]]></Body>
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```

```
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if (moneyMade > 0) {
    for (int i = 0; i< fdSuperChargers.size(); i++) {
       superChargerMoney = superChargerMoney + "\nSuper Charger " + i + " made $" +
fdSuperChargers.get(i).moneyMade;
    }
}

String carsLooking = "\nCars looking for chargers currently: " + carsLookingForChargers;
String freeChargersString = "\nChargers currently not in use: " + freeChargers;
String carsParked = "\nCars parked because of not being able to find a charger: " +
carsNotCharged;

return carsLooking + freeChargersString + carsParked + superChargerMoney;]]></Body>
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if (nearestFree != null) {
    moveTo(nearestFree);
}]]></EntryAction>
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                                  <FillColor/>
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```

```
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```
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```

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```
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double carX = this.getX();
double carY = this.getY();

double minDist = 1000999900;
double dist;

for (int i = 0; i < superChargersList.size(); i++) {
    if (!superChargersList.get(i).full) {
       double chargerX = superChargersList.get(i).getX();
       double chargerY = superChargersList.get(i).getY();

       dist = sqrt(carX * chargerX + carY * chargerY);

       if (dist < minDist) {
             nearestFree = superChargersList.get(i);
             minDist = dist;
       }
    }
}
```

```
return nearestFree;]]></Body>
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//updateMoneyMade();]]></Body>
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```

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