Report

Title: Electric cars adoption throughout the years and in the future: A System Dynamics

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1 Introductory Note:

This document's purpose is to explain the basic understanding of the processes and agents involved in the adoption of electric cars as a personal vehicle, by the population, nowadays and in the future.

Having said that, the approach used to better understand this subject was to create a fairly complex dynamic model with the Vensim [4, 5] technology, based on [1], and also, a simpler dynamic model [2], but with competitiveness between companies [3, 5] in mind.

2 Summary / Abstract

This document addresses the market's adoption of electric vehicles, in order to replace the fossil fuels vehicles for the sake of low pollution emission and a greener/cleaner environment [7]. Previous work on the subject is surveyed and an outline of the current state of the art is presented.

Several possible solutions are identified and evaluated, however the solution proposed is the implementation of two system dynamics approaches, where one's purpose is to simulate and forecast the scale of electric vehicles and the other's purpose is to study the competitiveness between electric vehicles manufacturers. Besides that, a brief analysis on the essential components of the system dynamics, such as charging time, fuel price, battery production emissions cost, electric annual emissions, etc., is also performed.

Based on the simulation results, this analysis lead to the following results:

- Government policies and incentives are the major promoter of the electric vehicle industry evolution;
- With the development and construction of more infrastructures for charging, helps tremendously in the market's adoption;
- Improving the existing battery systems, with the goal to improve electric vehicles performance and efficiency, will also attract more costumers;
- Charging and electric vehicle prices have an important role on the electric vehicles penetration.

3 Framework

Fortunately, society, in the recent years, has become really concerned with our environmental impact and is starting to push even harder the renewable energies, making pressure on companies and governments, resulting in subsidy policies, leaving behind the fossil fuels. Since about 30% of all CO2 emissions in OECD countries, and about 20% worldwide, in 2000, just for the transportation sector [6], and because, nowadays, it remains identical, the market demand for alternatives to the conventional vehicles is swiftly increasing, and, consequently, the number of electric vehicles produced is still rising, making vehicle manufacturers speed up their electric vehicle production.

As I identify myself in the group of people that really cares about the environment, and finds curious the appearance and business strategy of companies like Tesla, I decided to study the electric vehicles market to determine if it is worth or not to buy an electric car.

4 System Dynamics Model for Scale Evolution of Electric Vehicles

As mentioned above, this document studies two system dynamics models, so in this section, it will be addressed the factor selection and the model for the scale evolution study of Electric Vehicles. For a better understanding of the model, a proposed case study about a hypothetical case in Portugal is described.

4.1 Factor Selection

Given that the model is based on [1], although the factors' selection are identical, there are a few additional factors that are taken in consideration, because I found them as important as the already implemented. Since the factors that influence the act of purchasing an electric vehicle are countless, it would be unreasonable to include them all in a system dynamics model, so the additional factors chosen were related with the environmental buzz that is happening over the recent years, also making me take interest on the subject.

As illustrated in [1] and adding the additional factors, a table with all the factors that may impact the market's evolution of electric vehicles is implemented, as shown in Table 1.

Classification	**Factor Item Set**
performance	range, charging time, vehicle lifetime, fuel efficiency, driving comfort, security, charging available, etc.
price	purchase price, price difference, fuel price, electric charging price, etc.
policies	government policy, subsidy, tax, etc.
psychology	electric annual emissions, battery production emissions cost, electric vehicle production emissions cost, etc.
others	GDP, population, etc.

Table 1: Factors considered as variables in the System Dynamics Model.

Upon choosing the important factors for the model, still remains the construction of relationships between them. Some are obvious mathematical relationships, while others, more related to psychological aspects, are complex to formulate. As referenced in [1], a survey-based method was adopted to help determine this complex relationships.

This survey was based on a questionnaire, where each of the questions were related to a different factor and as answers, 5 psychological options. The survey was conducted among young college Chinese graduates, in certain conditions, and provided 200 valid surveys.

From those 200 surveys, in order to summarize the results obtained, the question “If you were considering buying an Electric Vehicle, what is your main concern?” was taken into account, and a system of ranks was created, representing the importance given to each of the following factor items:

- Range;
- Charge Time;
- Price Difference;
- Purchase Price;
- Fuel Price.

Therefore, an illustration of the results obtained, based on that question, is shown in Figure 1.

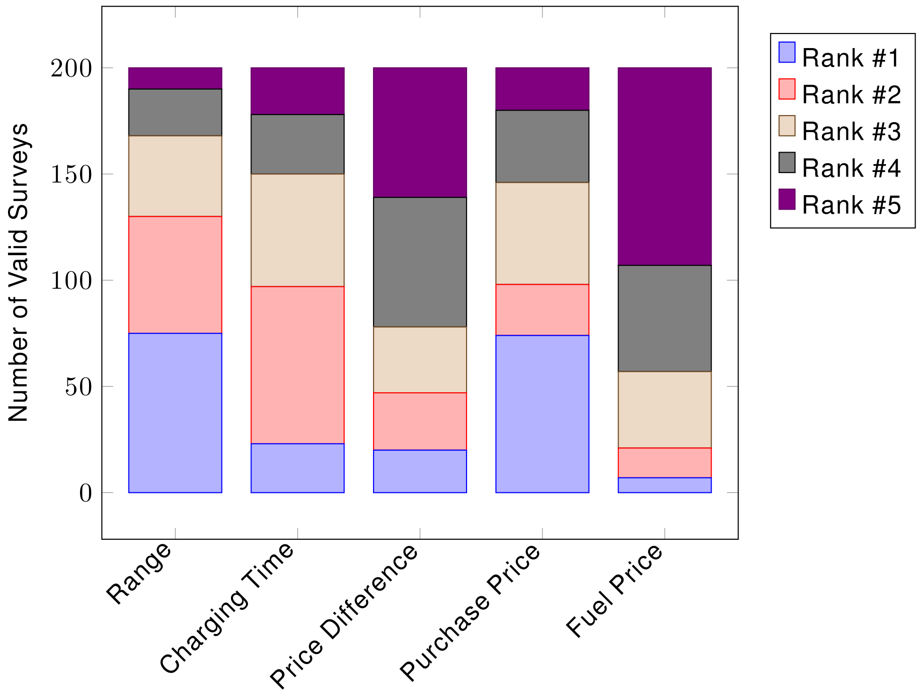

Figure 1: Factor Importance Distribution.

4.2 Proposed System Dynamics Model

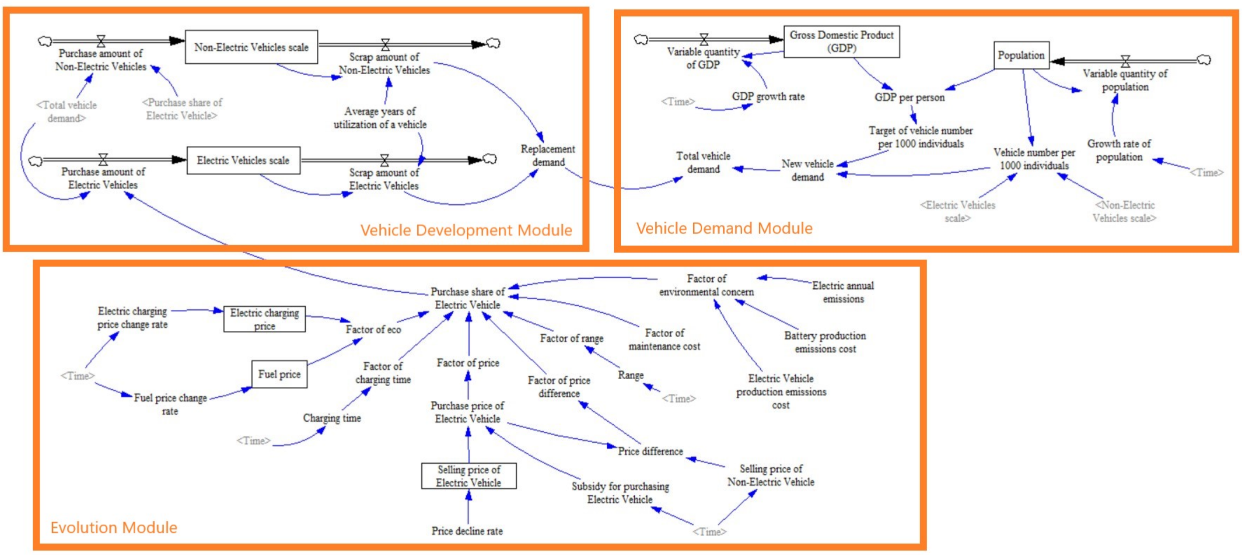

Figure 2: Stock and Flow Diagram.

Once the factors and relationships between them are settled, the designed model is composed by three modules, namely Vehicle Development module, Vehicle Demand module and Evolution module as displayed in Figure 2. Briefly, the Vehicle Development module portrays the development and the relationship between Non-Electric Vehicles and Electric Vehicles, the Vehicle Demand module exhibits the impacts of vehicles' utilization lifetime, and the Evolution module illustrates the relations among the factors which affect the Electric Vehicle adoption.

4.2.1 Vehicle Development Module

This module is appointed by the increase of vehicle demand and replacement, and is represented by the interplay between the vehicle scale and its increment or scrap. Because we are comparing two different types of vehicles, Electric and Non-Electric Vehicles, the module is partitioned in two groups. We will use the same business model as [1], which are translated to the following mathematical formulas:

$$EV_{parc}(t) = \sum_{t=0}^{T}(B_{EV}(t) - D_{EV}(t)) + EV_{parc}(t_0) \tag{1}$$

$$NEV_{parc}(t) = \sum_{t=0}^{T}(B_{NEV}(t) - D_{NEV}(t)) + NEV_{parc}(t_0) \tag{2}$$

$$D_{EV}(t) = \begin{cases} \frac{EV_{parc}(t)}{AVG}, & t \geq delay \\ 0, & t < delay \end{cases} \tag{3}$$

$$D_{NEV}(t) = \frac{NEV_{parc}(t)}{AVG} \tag{4}$$

The equation (1) illustrates the Electric Vehicles scale, which indicates the number of Electric Vehicles at time t, and is calculated by the purchase amount of Electric Vehicles ($B_{EV}(t)$) and the scrap amount of Electric Vehicles (3). Likewise, the equation (2) represents the Non-Electric Vehicles scale at time t. The purchase amount of Electric and Non-Electric Vehicles at time t is achieved according to the Electric and Non-Electric Vehicles scales, and the respective average utilization life-time factor. Whereas at the initial stage of Electric Vehicles development, there wasn't a large number of scrapped Electric Vehicles, so time delay is introduced as "$delay$" in (3).

4.2.2 Vehicle Demand Module

This module is characterized by the interactions between socio-economic development, demand for vehicles and Electric Vehicle scale. Like in the Vehicle Development module, the relationships are the same as [1], and are expressed as the following mathematical equations:

$$POP(t) = \sum_{t=0}^{T} PV(t) + POP(t_0) \tag{5}$$

$$PV(t) = POP(t) * PRT(t) \tag{6}$$

$$C_{GDP}(t) = \sum_{t=0}^{T} C_G(t) + C_{GDP}(t_0) \tag{7}$$

$$C_G(t) = C_{GDP}(t) * GR(t) \tag{8}$$

$$VP(t) = \frac{EV_{parc}(t) + NEV_{parc}(t)}{POP(t)} \tag{9}$$

$$ND(t) = (VPT - VP(t)) * \alpha \tag{10}$$

$$TD(t) = D_{EV}(t) + D_{NEV}(t) + ND(t) \tag{11}$$

Equations (5)-(6) illustrate the population dynamics, and the equations (7)-(8) exhibit the GDP variations. Equation (9) is the vehicle increment and it is measured by the ratio relation between the demand factor, and the differential of the number of vehicles per 1000 individuals (equation (9)) and the target of the number of vehicles per 1000 individuals (VPT), thus obtaining the equation (11).

4.2.3 Evolution Module

Although this module is still based on [1], unlike the other modules, this one has additional factors, which are mentioned in section 4.1. Therefore, this module portrays the Electric Vehicles purchase share (12), that is determined by the six subsequent factors, which are affected by $EV_R(t)$, $EV_T(t)$, $P_{EV}(t)$, $EV_{CS}(t)$, $P_{EV-NEV}(t)$, MC and $EC_{EV}(t)$ respectively:

- “Factor of Range”;
- “Factor of Charging Time”;
- “Factor of Price”;
- “Factor of Eco”;
- “Factor of Price Difference”;
- “Factor of Maintenance Cost”;
- “Factor of Environmental Concern”.

$$EV_{buy}(t) = EV_R(t)^{\beta_1} * EV_T(t)^{\beta_2} * P_{EV}(t)^{\beta_3} * EV_{CS}(t)^{\beta_4} * P_{EV-NEV}(t)^{\beta_5} * MC^{\beta_7} * EC_{EV}(t)^{\beta_7} \tag{12}$$

With the equation (12), β_i is introduced and constitutes the weight assigned to each factor, reflecting the relationships' significance among factors. Due to the business model's subjectivity, a linguistic weight decision method [1] was used to predict the value of β_i, under the survey's rank results shown in Figure 1. Therefore, the following equation is formulated:

$$\beta_k = \frac{\sum_j people_{j,k} l_j}{\sum_{j,k} people_{j,k} l_j} \tag{13}$$

where, $l_j = j$ in the j_{th} rank, and $people_{j,k}$ is the number of people that evaluates the k_{th} factor with the j_{th} rank. The table 2 showcases the weight of each factor, bearing in mind the results shown in Figure 1 and the equation (12).

Factor	$EV_R(t)$	$EV_T(t)$	$P_{EV}(t)$	$EV_{CS}(t)$	$P_{EV-NEV}(t)$	MC	$EC_{EV}(t)$
β_i	0.254	0.216	0.223	0.134	0.162	0.102	0.235

Table 2: Factors and its corresponding assigned weight.

Every factor affecting the purchase share of Electric Vehicles, requires a formula/equation to reflect the relationships between them. So, considering the formulation process of "Factor of Price" in Figure 1 as an example, the purchase price of an Electric Vehicle is equal to the selling price of an Electric Vehicle minus the subsidy for purchasing the Electric Vehicle, leading to the following equation:

$$P_{EVp}(t) = P_{EVsell}(t) - P_{EVsub}(t) \tag{14}$$

To formulate the equation (15), which indicates the percentage of people, from the 200 valid surveys, that would buy an Electric Vehicle taking into account the various price ranges, a function fitting based on the question "If you were considering buying an Electric Vehicle, in which of the following price ranges would you be shopping?" results was employed.

$$P_{EV}(t) = \begin{cases} 100\%, & P_{EVp}(t) < 15 \\ 56.5\%, & 15 \leq P_{EVp}(t) < 23 \\ 18.5\%, & 23 \leq P_{EVp}(t) < 31 \\ 6.5\%, & 31 \leq P_{EVp}(t) < 38 \\ 1\%, & P_{EVp}(t) \geq 38 \end{cases} \tag{15}$$

To briefly explain equation (15), using the last interval as an example, it states that if the purchase price of an Electric Vehicle is higher than 38x10^3€, less than one percent of people that responded to the survey will buy an Electric Vehicle. The equation (16) emphasizes the importance of the environmental concern about Electric Vehicles at time t, where the $E_{annual}E(t)$ corresponds to the electric annual emissions produced, the $B_{prod}E(t)$ represents the battery production emissions cost and the $EV_{prod}E(t)$ depicts the Electric Vehicle production emissions cost. Lastly, the MC is the maintenance cost of an Electric Vehicle per year, thus a constant.

$$EC_{EV}(t) = E_{annual}E(t) * B_{prod}E(t) * EV_{prod}E(t) \tag{16}$$

5 Proposed Case Study

5.1 Case Description

To evaluate the market and validate the System Dynamics model, it is proposed to use Portugal as an example. Since the Electric Vehicle market in Portugal is still in the beginning, it is a fine location to study the model. Therefore, some initial values of the related parameters for the simulation are illustrated in Table 3. The average usage of the vehicles is set to 10 years. To simplify, the Gross Domestic Product and Population growth rate are set to 0.0017, and the "delay" function in equation (3) is set as 50 months. Finally, the initial time would be 0 (year of 2019) and the end time equal to 240 (year of 2039).

Variable	Initial Value	Unit
Electric Vehicles scale	2000	
Non-Electric Vehicles scale	384705	
Fuel Price	1.4	Euro/Litre
Electric Charging Price	0.23	Euro/Litre
Subsidies for Purchasing an Electric Vehicle	2250	Euro
Selling Price of an Electric Vehicle	50	x10^3 Euro
Selling Price of an Non-Electric Vehicle	25	x10^3 Euro
Price Decline Rate per Month	0.008	Percentage
Population	1.02766e+07	People
GDP	2.09035e+11	Euro
Charging Time	1.5	Hour
Range	400	Km
Target of the Number of Vehicles per 1000 Individuals	400	Vehicles
Electrical Annual Emissions	5000	Kg CO2
Battery Production Emissions Cost	12000	Kg CO2
Electric Vehicle Production Emissions Cost	10000	Kg CO2
Factor of Maintenance Cost per year	625	Euro

Table 3: Parameters' Initial Value.

6 System Dynamics Model for Analysis of the competitiveness between Vehicles manufacturers

Completed the analysis on the Electric Vehicles scale, we will carry on the study about the Electric Vehicles market, but now with a competitive landscape. Similarly to the section 4, a brief explanation about the designed model and its variables will be conducted, and a simulation example with Portuguese numbers will be performed in the section 7 to validate the System Dynamics model.

6.1 Proposed System Dynamics Model

In comparison to the model in Figure 2, this model is simpler, because it was created to help understand the competitiveness between automobile manufacturers, and so does not need the additional complexity. The model tries to replicate a market composed by three competitors (A, B and C) as shown in Figure 3. Each of the competitors is composed by a few variables:

- "Automobile manufacturer" - Number of people that buy an Electric Vehicle and adhere to the company;
- "Automobile manufacturer behaviour" - Value that represents the market's impact on the company;
- "Initial Adopters" - Number of people that, in the beginning, already bought an Electric Vehicle;
- "Relative Quality" - Value that represents the Electric Vehicle quality when compared to the market's average quality, also takes into consideration the market's change;
- "'Quality" - Value that represents the Electric Vehicle quality based on the range, top speed, power and selling price of the Electric Vehicle;
- "Range" - Number of Km that the Electric Vehicle can do with a full charge;
- "Top speed" - Highest velocity, in Km/h, that the Electric Vehicle can achieve;
- "Power" - Quantity of energy transferred/converted, in kW;

- “Selling price” - Amount, in Euros, that an Electric Vehicle costs;
- “Average Quality” - Value that represents the average quality practiced by the market.

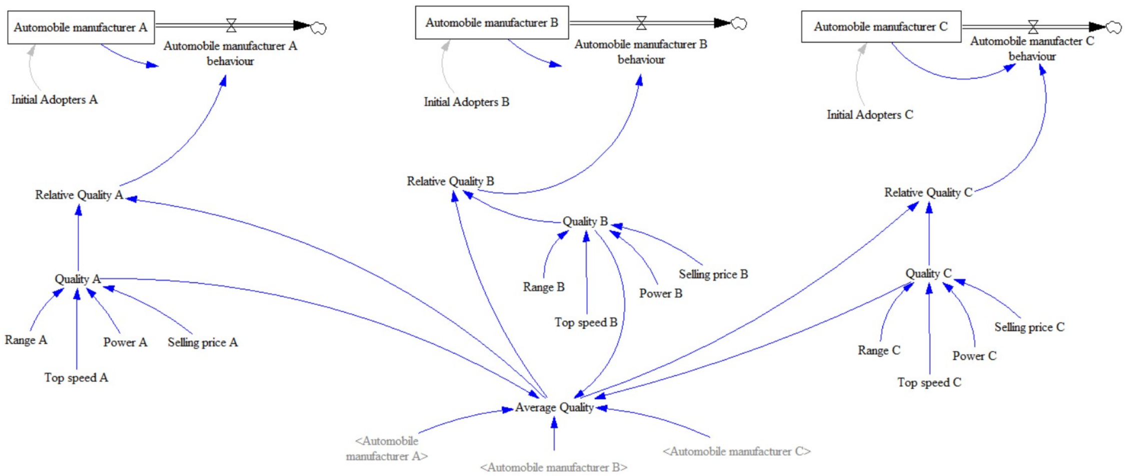

Figure 3: Stock and Flow Diagram.

7 Case Study

7.1 Case Description

Let’s now assume that we are in Portugal and have an Electric Vehicle market with 10750 individuals. In the beginning, the automobile manufacturer A has 700 adopters, the automobile manufacturer B has 10000 adopters and the automobile manufacturer C has 50 adopters. The Table 4 illustrates, in detail, the model’s approach to this market. The time interval set is 1 year (12 months).

The equation formulated to obtain the quality value is composed by the $LOG(x, 10)$ function in order to lower the final value, and the multiplication between the “Range”, “Top speed” and “Power” variables has the purpose of favouring those attributes, while the division by the “Selling price” intends to prejudice the final result.

Variable	Equation/Initial Value	Unit
Automobile manufacturer A	= INTEG(Automobile manufacturer A behaviour, Initial Adopters A)	People
Automobile manufacturer B	= INTEG(Automobile manufacturer B behaviour, Initial Adopters B)	People
Automobile manufacturer C	= INTEG(Automobile manufacturer C behaviour, Initial Adopters C)	People
Automobile manufacturer A behaviour	= Automobile manufacturer A * Relative Quality A	
Automobile manufacturer B behaviour	= Automobile manufacturer B * Relative Quality B	
Automobile manufacturer C behaviour	= Automobile manufacturer C * Relative Quality C	
Initial Adopters A	700	People
Initial Adopters B	10000	People
Initial Adopters C	50	People
Relative Quality A	= (Quality A / Average Quality) - 1	
Relative Quality B	= (Quality B / Average Quality) - 1	
Relative Quality C	= (Quality C / Average Quality) - 1	
Quality A	= (LOG(Power A, 10) * LOG(Range A, 10) * LOG(Top speed A, 10)) - LOG(Selling price A, 10)	
Quality B	= (LOG(Power B, 10) * LOG(Range B, 10) * LOG(Top speed B, 10)) - LOG(Selling price B, 10)	
Quality C	= (LOG(Power C, 10) * LOG(Range C, 10) * LOG(Top speed C, 10)) - LOG(Selling price C, 10)	
Range A	409	Km
Range B	300	Km
Range C	400	Km
Top speed A	225	Km/h
Top speed B	144	Km/h
Top speed C	200	Km/h
Power A	211	kW
Power B	110	kW
Power C	125	kW
Selling price A	48900	Euro
Selling price B	35400	Euro
Selling price C	85771	Euro
Average Quality	= ((Quality A * Automobile manufacturer A) + (Quality B * Automobile manufacturer B) + (Quality C * Automobile manufacturer C)) / (Automobile manufacturer A + Automobile manufacturer B + Automobile manufacturer C)	

Table 4: Equations and Initial Values of the Variables.

7.2 Simulation and Discussion

Once the parameters are established and the simulation is executed, the simulation results displayed in Figure 4 illustrate the market's evolution in 1 year, and conclude that, although the automobile manufacturer C manages to conquer the trust of 35 additional individuals in the first 6 months, the only automobile manufacturer that has a continuous growth is the automobile manufacturer A, achieving a peak of 9500 people, nearly taking all the market share. By contrast, the automobile manufacturer B has a continuous decline, going from 10000 to 1000 people. It is also noteworthy that Vensim scales each variable, which is why the Figures 4 and 6 have 3 values on the y axis.

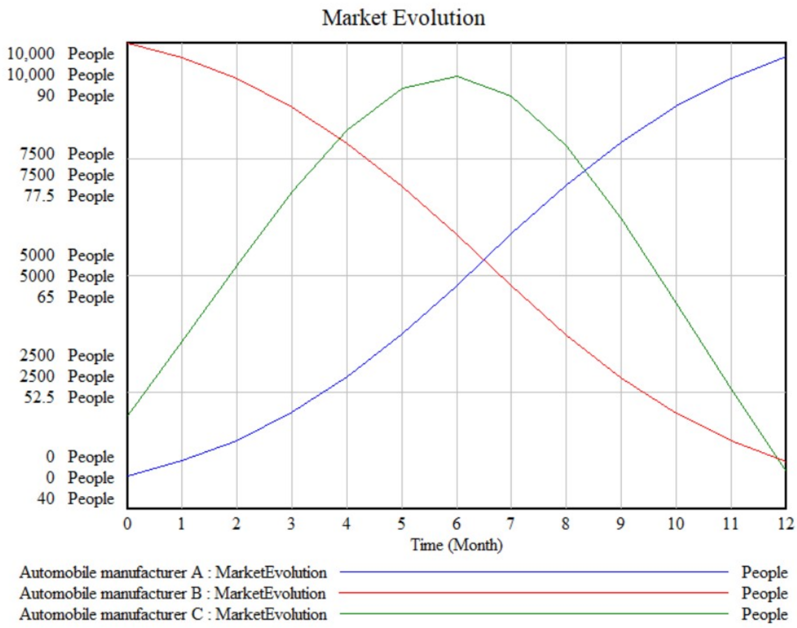

Figure 4: Market's Evolution in 1 year.

As people shifts from one manufacturer to another, the average quality of the market is continuously growing in a slight pace as shown in Figure 5, because as the market moves to a manufacturer that offers an Electric Vehicle with better quality, the market expectations also increase, becoming more demanding.

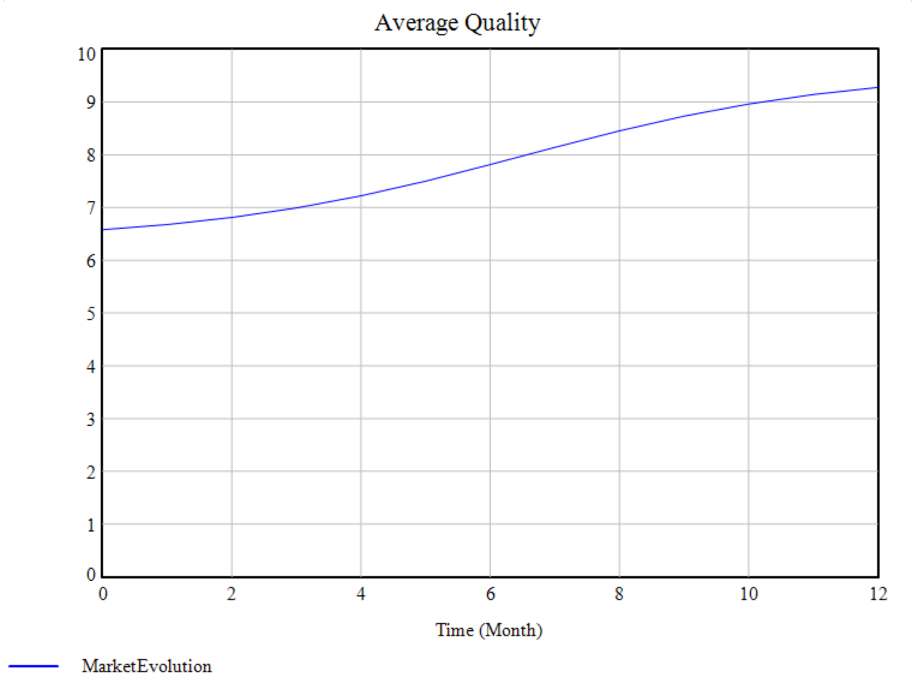

Figure 5: Market's Average Quality Growth in 1 year.

Lastly, the relative quality results, shown in Figure 6, illustrate that all the automobile manufacturer have a diminishing relative quality, due to the fact that the quality of the Electric Vehicles is the same throughout the year, because its the same Electric Vehicle, while the average quality is continuously growing.

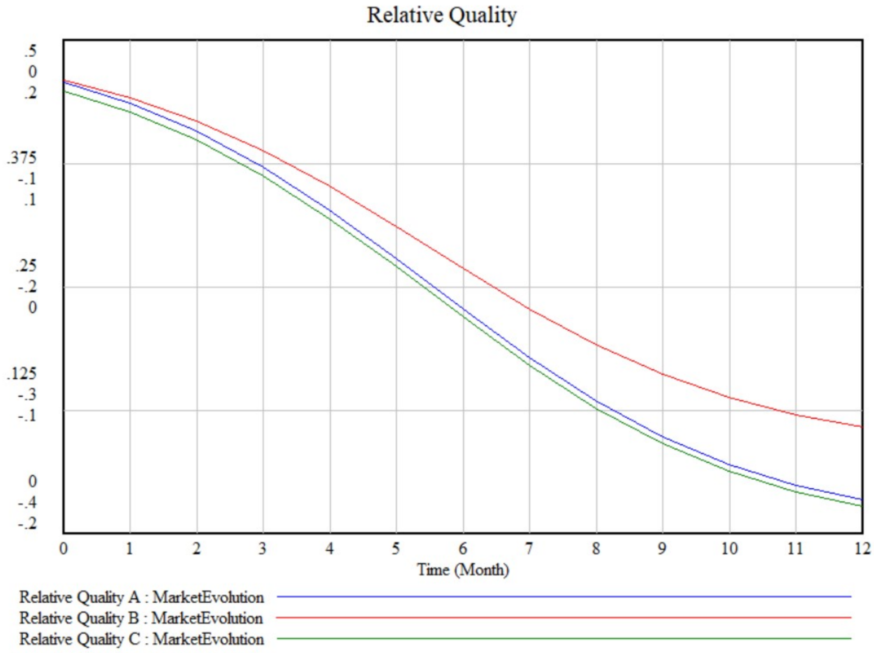

Figure 6: Relative Quality Progression in 1 year.

Even though it is easy to conclude that the automobile manufacturer with the best offer is the automobile manufacturer A and, consequently, would eventually take up all the market share, in the real world, the behaviour of the market is much more complex and unpredictable, because factors like, purchasing power or personal taste, are taken into consideration, which require a more sophisticated model.

Nevertheless, the proposed model is a good foundation to help better understand the competitiveness between companies.

8 Conclusions

From what has been presented in this document it can be concluded that when studying the market, some indispensable relationships between factors can only be formulated with the consumers' opinion, and that is why, sometimes, surveys occur. Taking into account the model in Figure 2 and the simulation results on [1], although nowadays has been improving, the evolution of the Electric Vehicles is quite restricted, mainly because of the low level of technology currently available on the market and the insufficient infrastructures.

It is also possible to conclude that the major factor to help encourage and promote the development of Electric Vehicles is the government policies and subsidies, which agrees with nowadays reality. So, as the technology and infrastructures improve over time, the market will be dominated by Electric Vehicles.

Turning now to the model in Figure 3 and analyzing the simulation results achieved in section 7.2, as already stated above, it doesn't take a long time for the consumers to realize and start to adopt the better offers available in the market, even though they aren't adopted at an initial stage.

It still remains to implement and execute a simulation about the proposed case study described in section 5, and, for example, transpose a model with a similar complexity as the one in Figure 2, to the model in Figure 3, making it more sophisticated and realistic, would be interesting to consider as future work.

9 References

[1] Yue Xiang, Hao Zhou, Wei Yang, Junyong Liu, Yi Niu, Jiahui Guo, "Scale Evolution of Electric Vehicles: A System Dynamics Approach", 2016, Available online [17/06/2019]: https://ieeexplore.ieee.org/document/7914729.

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[3] Craig W. Kirkwood, "New Product Dynamics, Illustrative System Dynamics Models", 1998, Available online [17/06/2019]: https://www.public.asu.edu/~kirkwood/sysdyn/NewProd.pdf.

[4] Ventana Systems, Inc, Vensim, Available online [17/06/2019]: http://vensim.com/vensim-software/.

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[6] Malcolm A. Weiss, John B. Heywood, Elisabeth M. Drake, Andreas Schafer, Felix F. AuYeung, "ON THE ROAD IN 2020: A life-cycle analysis of new automobile technologies", 2000, Available online [17/06/2019]: https://energy.mit.edu/publication/on-the-road-in-2020-a-life-cycle-analysis-of-new-automobile-technologies/.

[7] Martin Eberhand, Marc Tarpenning, "The 21st Century Electric Car", 2006, Available online [20/06/2019]: http://www.evworld.com/library/Tesla_21centuryEV.pdf.

10 Useful Web Links

https://www.youtube.com/watch?v=0JsI9ZYPS54;

https://data.worldbank.org/indicator/EN.CO2.TRAN.ZS;

https://www.reuters.com/article/us-toyota-electric/toyota-speeds-up-electric-vehicle-schedule-as-demand-heats-up-idUSKCN1T806X;

https://www.youtube.com/watch?v=6RhtiPefVzM.

11 Nomenclature

$EV_{parc}(t)$	Electric Vehicle scale at time t
$B_{EV}(t)$	Purchase amount of Electric Vehicles at time t
$D_{EV}(t)$	Scrap amount of Electric Vehicles at time t
$NEV_{parc}(t)$	Non-Electric Vehicles scale at time t
$B_{NEV}(t)$	Purchase amount of Non-Electric Vehicles at time t
$D_{NEV}(t)$	Scrap amount of Non-Electric Vehicles at time t
AVG	Average usage, in years, of a vehicle
$POP(t)$	Population at time t
$PV(t)$	Variable quantity of population at time t
$PRT(t)$	Growth rate of population at time t
$C_{GDP}(t)$	Total quantity of Gross Domestic Product at time t
$C_G(t)$	Variable quantity of Gross Domestic Product at time t
$GR(t)$	Growth rate of Gross Domestic Product at time t
$VP(t)$	Vehicle number per 1000 people at time t
$ND(t)$	New vehicle demand at time t
VPT	Target of vehicle number per 1000 people
α	Demand factor
$TD(t)$	Total vehicle demand at time t
$EV_{buy}(t)$	Purchase share of Electric Vehicles at time t
$EV_R(t)$	"Factor of Range" at time t
$EV_T(t)$	"Factor of Charging Time" at time t
$P_{EV}(t)$	"Factor of Price" at time t
$EV_{CS}(t)$	"Factor of Eco" at time t
$P_{EV-NEV}(t)$	"Factor of Price Difference" at time t
MC	"Factor of Maintenance Cost" t
$EC_{EV}(t)$	"Factor of Environmental Concern" at time t
$E_{annual}E(t)$	Average electric annual emissions at time t
$B_{prod}E(t)$	Average battery production emissions cost at time t
$EV_{prod}E(t)$	Average Electric Vehicle production emissions cost at time t
β_i	Weight value of factor i
$people_{j,k}$	Number of people who evaluated the k_{th} factor with the j_{th} rank
$P_{EVp}(t)$	Purchase price of an Electric Vehicle at time t
$P_{EVsell}(t)$	Selling price of an Electric Vehicle at time t
$P_{EVsub}(t)$	Subsidy for purchasing an Electric Vehicle at time t
$P_{FUEL}(t)$	Fuel price at time t