Sharing the Total Cost of Ownership of Electric Vehicles: A Study on the Application of Game Theory

Hugo G. Chalé G.
RENAULT
1 avenue du Golf
78288 Guyancourt, France

Abdelkrim Doufene, Daniel Krob
Ecole Polytechnique
Laboratoire d'Informatique (LIX)
91128 Palaiseau Cedex, France

Abstract. In this paper, we present the contribution of game theory to the search of architectural equilibrium in the context of complex systems engineering. Our design approach is based on the use of an architectural design framework and of optimization models, illustrated by a practical example in which the system of interest is a commercial electric vehicle in its ecosystem. We rely on systems engineering in order to clearly understand the system we want to study and its environment, during the entire life cycle of the system. For interdependent decisions between stakeholders in the lifecycle of the system, the concept of equilibrium is important. Architectural equilibrium of the system guarantees its integration in its environment, the stability of the environment and the satisfaction of all stakeholders. This is modeled as a game in the sense of game theory leading to a Nash equilibrium, which allows anticipating for changes in an uncertain environment (departure of a stakeholder, arrival of a new actor, changes in requirements or constraints and so on).

Introduction

The global economic crisis and world-wide competition make Original Equipment Manufacturers (OEM) strive to differentiate their products from those of competitors through the integration of innovations, while reducing production costs, in order to ensure their position in different markets. Like in other industries, car manufacturers are also affected by the services-oriented "post industrial" era. They also have to deal with environmental problems such as air pollution and decreasing of fossil fuels stocks, which make their prices increase. Thus, car manufacturers offer more and more environmentally friendly vehicles and, now, services that incorporate many innovations and new technologies.

Innovations in this context not only stem from a single company, but they are increasingly the result of collaborations between companies from different backgrounds. The Electric Vehicle (EV) is an interesting example. From the point of view of a traditional customer, EVs appear to be more expensive compared to internal combustion vehicles in the same category. In some contexts and for some OEMs, this fact is indeed true if we consider only the purchasing price. However, these new type of vehicles needs to be studied in a larger scope mixing vehicles and infrastructure. They must be studied in the context of their entire life cycle, and their Total Cost of Ownership, from the perspective of a "System of Systems" in the sense that we must take into consideration several interdependent stakeholders and constituent systems (customers, vehicle producers, energy suppliers, telecommunication operators, states and local governments, financial institutions, etc.).

Given the complexity of such systems and the difficulty to introduce them successfully into the market, it is important to define an effective approach to deal with all the problems around them. Indeed, the integration of a new system in a given environment can disturb the stability of this environment and cause adverse or unexpected events, which in turn can hinder the success of the new system. This integration is becoming increasingly difficult due to the complexity of the system of interest (SOI) and of its environment.

To address this problem, we propose in this paper a design approach based on systems engineering (SE) principles and game theory, illustrated by a practical example for electric vehicles. We rely on systems engineering in order to clearly understand the system we want to study (EV) and its environment, during the entire life cycle of the system. The purpose is to find a global balance between stakeholders that meets all their needs (or satisfies their strategies) and to take into account feasibility constraints (economic, technological, regulatory, and social). This guarantees a better integration of the SOI in its environment and the stability of this environment. This is modeled as a game in the sense of game theory, which allows anticipating for changes in an uncertain environment (departure of a stakeholder, arrival of a new actor, changes in requirements or constraints and so on).

Why systems engineering?

In the concept stage of a complex system, the identification of all stakeholders whose participation is essential to the success of the system is of outmost importance. Decisions made at this stage guarantee or jeopardize the successful integration of the system in its environment. Different types of decisions can be considered. One can imagine many possible decisions based on the needs of stakeholders, their strategies often interdependent, the total cost of ownership (TCO) or Measures Of Effectiveness (MOEs) of the system. These decisions generate the initial guidelines for choosing architectures and acceptable levels of attainment of properties during the life cycle of the system such as quality, reliability, security, flexibility, robustness , scalability and sustainability. Feasibility studies in economic, technical, social and regulatory fields are thus essential to meet the needs of all stakeholders around the system of interest.

In industrial practice, however, several multidisciplinary objectives and constraints come into play in the design of a complex system. Conducting analysis, identifying the right evaluation criteria and evaluating possible alternatives are difficult tasks. This difficulty is particularly due to the fact that the separation between the problem definition and the design of a solution is often blurred.

Using an architectural design framework could significantly contribute to fill this gap, and to clarify the relationship between design constraints and design variables, often mixed in practice. Architectural design frameworks offer guides and rules to structure and organize system architectures. The views and viewpoints that cover all the system architecture and the different abstraction levels clearly separate the problem space and the solution or design space. Using a framework helps achieving a complete modeling of all aspects of the system, by studying the system in stages in an iterative manner and by highlighting elements such as the system scope, environment, purpose, missions, goals, stakeholders, etc. Once these elements are clearly identified, we can then design the SOI and describe it according to different viewpoints. In our study, we use three main viewpoints as explained in (Krob, 2009 and 2010) and (Doufene et al., 2012):

- **The operational viewpoint** serves to define why the system should be built, i.e. to clarify the relationship between the system and the elements of its environment (other systems, actors), as well as its missions and the services it offers.
- **The functional viewpoint** serves to explain how the system works (its functioning) or what the system has to do.
- **The structural viewpoint** serves to define what the system will be made of, how it will be physically structured (i.e., the physical organization of its components -hardware, software and human-).

Why game theory?

Game theory is a theory of decision of rational and strategically interdependent agents. The games studied in game theory are well-defined mathematical problems. A game consists of a set of players, a set of strategies available to those players, and a specification of payoffs for each combination of strategies. Games are interactive decision situations in which the utility (welfare) of each individual depends on the decisions of other individuals (Koessler, 2008).

As stated in (Guerrien, 2010), the ingredients of a game are a list of n individuals called players, designed to maximize an objective function (or gain, quantified in one way or another) given the information they have on other players. Each player has a set of strategies often represented by the values of gains of each player in the game. A solution of the game is a result of a combination of strategies.

Explanation through a simple example. This example taken from (Penard, 2004) is slightly modified and adapted in order to illustrate the terms we will use in this paper. Let us take two car makers (players) OEM1 and OEM2. Let us assume that they produce very similar cars so that the price remains the only variable the consumer takes into account when buying a car. The numbers in each cell of table1 are the benefit of OEM1 and OEM2 respectively. Each company has two possible strategies for the pricing of its cars: set a high price or a low price. The scoring matrix indicates the monetary consequences of these different pricing strategies for each business. Note that if OEM1 and OEM2 both set a high price, we are in a bad situation from the consumer viewpoint; each firm obtains a higher profit (450 million Euros to OEM1 and 400 million for OEM2). However, if one of the companies sets a high price, the other can get a bigger profit by lowering its price (by deviating from the strategy of high price) (700 million Euros to OEM1 or 600 million Euros for OEM2) and leaves his rival a profit of 100 million Euros. If both firms set a low price, they earn only 300 million Euros for OEM1 and 250 million for OEM2.

Table 1. The normal form (or strategic form) of the first example of game.

		OEM2	
		Low Price	High Price
OEM1	Low Price	300, 250	700, 100
	High Price	100, 600	450, 400

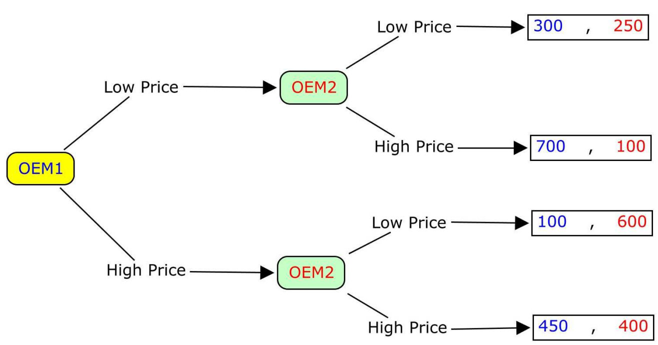

Figure 1. The extensive form of the game.

In table1, the only combination of strategies leading to a ***Nash*** equilibrium (a game outcome in which no player has an incentive to change his strategy given the strategies of the other players) is when OEM1 and OEM2 set both a low price and get a profit of respectively 300 and 250 million Euros. This is the only combination of strategies leading to a balance, despite the fact that both companies would rather have a common interest in setting high prices. But the combination of the strategies of high prices could encourage one of the firms to deviate.

The low price equilibrium can be justified in another way. We can indeed notice that setting a low price is the best choice for each company regarding the choice of his rival. When a player's strategy is best response to all possible strategies of his rivals, we say it is a dominant strategy (the low price strategy in this example). The equilibrium of this game is so called dominant strategy equilibrium. Note that, in principle, a rational player should never use a dominated strategy (a strategy that yields the lowest gains given all the possible strategies of his rivals).

If we use the formal terms used in game theory, we can express this example as follows:

We have a game with n = 2 players. Player1 is OEM1 and player2 is OEM2.

S1 = {S1a, S1b} is the set of strategies of the player OEM1 where S1a is the low price strategy and S1b is the high price strategy.

S2 = {S2a, S2b} is the set of strategies of the player OEM2 where S2a is the low price strategy and S2b is the high price strategy.

The outputs of the gain function Π are:

- Π1 (S1a, S2a) = 300
- Π1 (S1a, S2b) = 700
- Π1 (S1b, S2a) = 100
- Π1 (S1b, S2b) = 450
- Π2 (S1a, S2a) = 250
- Π2 (S1a, S2b) = 100
- Π2 (S1b, S2a) = 600
- Π2 (S1b, S2b) = 400

The game equilibrium is given by the combination of strategies (S1a, S2a).

Note that in this example, the game is played with ***pure strategies***, that is to say we do not associate probabilities to strategies. However, in a game with ***mixed strategies***, we associate the probability that a strategy is chosen by the player.

If the gains of each player change as follows, we have a game that has no equilibrium using pure strategies.

Table 2. The normal form (or strategic form) of the second example of game.

		OEM2	
		Low Price	High price
OEM1	Low Price	300, 250	100, 100
	High Price	100, 100	250, 400

The set of possible mixed strategies in a game with 2 players is the set of all p, $0 \leq p \leq 1$ and the set of all q, $0 \leq q \leq 1$. If the players have n pure strategies, a mixed strategy is a probability distribution over all these strategies, that is to say all vectors $p = (p1, ..., pn)$ where $p1 \geq 0, p2 \geq 0, ..., pn \geq 0$ and $p1 + p2 + ... + pn = 1$. (Penard, 2004)

In our example, if the strategy chosen by OEM1 is Low Price with probability p then the high price strategy will have a probability $1-p$. If the strategy chosen by OEM2 is low price with probability q then the high price strategy will have a probability $1-q$.

Gains of each player are calculated in terms of expected gains (utility). The expected value of a strategy is the expected gain to receive, weighted by the probability of choosing of the other player.

For OEM1, the expected gains in high-price strategy are **q * 250 + (q-1) * 100.** The expected gains in low price strategy are **q * 100 + (q-1) * 300.**

For OEM2, the expected gains in high-price strategy are **p * 400 + (1-p) * 100.** The expected gains in low price strategy are **p * 100 + (1-p) * 250.**

Now, the mixed-strategy equilibrium is achieved when:

(1) The expected gains from OEM1 are equal (i.e. with low price or high price), that is to say, when **q * 250 + (q-1) * 100 = q* 100 + (q-1) * 300**. This equation gives the results **q = 4/7** and **1-q = 3/7**.

(2) The expected gains from OEM2 are equal (i.e. with low price or high price), that is to say, when **p * 400 + (1-p) * 100 = p* 100 + (1-p) * 250**. This equation gives the results **p = 1/3** and **1-p = 2/3**.

Then, the expected gains of OEM1 are **185.71 Euros** and the expected gains from OEM2 are **200 Euros.**

The calculation of Nash equilibrium in mixed strategies can be implemented using algorithms. We use an application developed as part of the work in (Chatterjee 2009). The author proposes an application that allows users to find Nash equilibrium of finite no-cooperative games for n players. For a review on algorithms for solving Nash equilibrium, we can refer to the literature review of (Daskalakis, 2008) where the author cites, for example, the Lemke-Howson algorithm (an algorithm for calculating equilibrium with 2 players) that can be generalized for multi-player games.

Link With Systems Engineering. As explained previously, one of the first steps of a systems engineering approach is to define the environment of the system of interest (SOI). This step serves to clearly differentiate the SOI from the systems with which it interacts in order to anticipate the evolution of external systems and their effect on the system and its environment. This allows the clearest possible view of the external interfaces of the SOI before diving into the optimization of its internal architecture. Note that the modeling phase of the environment is crucial: forgetting an external system or a stakeholder could jeopardize the design of the SOI, because, throughout the life cycle of the SOI, their needs are often interrelated.

More generally, all the data needed to mathematically formalize the optimization problem using game theory stem from the SE process activities supported by our architectural design framework. Likewise, the results of the optimization model are fed back to the SE process in order to update or modify, if necessary, the appropriate SE artifacts or objects (e.g. requirements, components…) resulting in an iterative spiral-like process in which the SE and optimization spaces feed each other back and forth. This might also mean that a technically optimized solution might not necessarily stand for the best “business strategy” in a given context.

In order to use the vocabulary SE and of game theory, each stakeholder might be regarded as a rational player around a system. Each has his own strategies to maximize his profits, which represent the satisfaction of his own needs. The designer of the SOI should seek to better satisfy stakeholders (players) by choosing a system architecture that represents an architectural equilibrium in the sense that it guarantees a stable environment throughout the SOI lifecycle. Finally, we can say that pre-dimensioning this equilibrium is a solution of a game where the players are the stakeholders. If one considers that stakeholders can build coalitions in the sense that they combine their choice of strategies, it is called cooperative game. Otherwise, it is a non-cooperative game.

In the following sections, we present a model of an optimization problem in order to satisfy all economic actors around the electric vehicle.

Application to the TCO of Electric Vehicles

The objective of our approach is to combine optimization techniques based on game theory with the systems engineering technical processes in order to establish an architectural equilibrium. To model our example as a game, the TCO of the EV will represent the total gain, the stakeholders will be the players and their business strategies the strategies they dispose of in the game.

We propose to model this problem as a general equilibrium model (with Nash equilibrium). This will help us find the values of the items used in the model (e.g., cost of energy, cost of telecommunications services, bank fees, bonuses, etc.). These values would be necessary and sufficient to assure the return on investments related to the electric vehicles compared to internal combustion engine vehicles, while satisfying the manufacturer of the vehicle, the customer and the various economic actors involved around the electric vehicles.

The approach can be outlined as follows:

1. Analysis of the environment of the SOI.
2. Identification Stakeholders.
3. Analysis of stakeholder needs and identification of MOE's. Focus on their business strategies and most important constraints.
4. Identification and formalization of the interdependence of strategies.
5. Analysis of the life cycle of the SOI and its TCO.
6. Formalization of a game using normal or extensive form, with the TCO being the total gain
7. Definition of distribution scenarios.
8. Search for equilibrium.
9. If coalitions are acceptable, imagine coalitions between stakeholders, Go to 7
10. Implement the equilibrium solutions.

First, we identified a set of stakeholders and highlighted important external interfaces through literature reviews gaining insight on the environment of the EV. Many stakeholders (customers, users, auto manufacturers, energy suppliers, financial institutions, telecommunication operators, parking, ...) are involved in the environment of the EV. Given the long list of external elements and in order to avoid ambiguities, we have listed the elements of the environment according to the "role" they play, as shown in Figure 2.

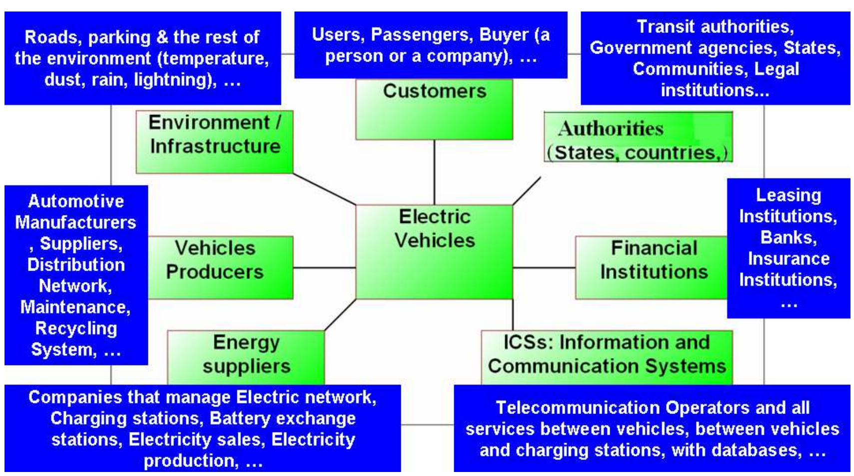

Figure 2. Ecosystem of electric vehicles.

Total Cost of Ownership. In order to calculate the Total Cost of Ownership (TCO) of the vehicle, we take into account the initial cost or acquisition cost, the cost of use related to energy consumption, the EV depreciation, the financial fees (credits and insurance) and the maintenance and repair costs. For comparison purposes, we begin by calculating the ownership costs breakdown of an Internal Combustion Engine Vehicle (ICEV) over five years, as shown in Figure 3.

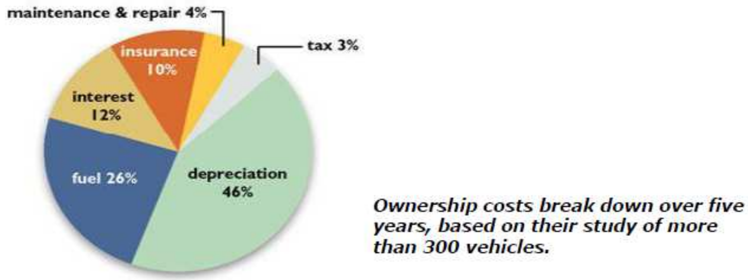

Figure 3. TCO of an internal combustion engine vehicle (ICEV) taken from www.ifmacentralpa.org [1] .

The initial cost includes costs such as the purchase price of the vehicle, the vehicle registration fees and interests (bank credit) where it is mandatory to consider the interest rate and the duration of the credit. It is also useful to consider governmental aid to purchase a vehicle depending on its CO2 emissions, like in some European countries.

Additionally, we consider various fees per month, including insurance, maintenance, cleaning, washing, penalties (speed, parking)), technical control, tolls, parking, the subscription to a communication service (internet, book charging terminals and / or remote parking, bill payment, remote access). For an ICEV, if penalties are envisaged on CO2 emissions, we will need an estimation of the vehicle emissions to determine the tax that will be imposed.

For calculating the costs of use related to energy consumption, a preliminary estimation of the number of kilometers per month and the duration of possession of the vehicle is useful. In the case of EVs, we consider the consumption, the price of 1 kWh/100km (which might change depending on the type of charging and the time of day) and the subscription for an electricity supply service. In addition, we can consider the monthly rent of the battery, if applicable. In the case of ICEVs, we consider the fuel consumption (1 l/100 km) and fuel prices (which can of course vary over time).

These variables and relationships are listed in table 4.

Table 4. Variables and mathematical relationships in order to calculate TCO.

Variables	Explanations	Mathematical formulations
EV_TCO	TCO of the electric vehicle given a number of months (Y1).	EV_TCO = F1+ (F2 + F4)*Y1
ICEV_TCO	TCO of an internal combustion engine vehicle given a number of months (Y1).	ICEV_TCO = F1+ (F3 + F4)*Y1 + G2
F1	Initial costs related to the purchase of the vehicle. All the variables are explained in this table.	F1 = ((X1 * (1+ X2) – X3 – X4 – X5) + (G1* X6) + X7+ X8+ X29
X1	Vehicle price before tax.	
X2	VAT (Value Added Tax)	
X3	Governmental bonus	
X4	Promotions	
X5	Amount of the credit	
X6	Number of months (of the credit)	

[1] http://www.ifmacentralpa.org/meetings/FACPLAN_IFMA_021512_Presentation.pdf (November 2012).

X7	Credit application fees	
X8	Costs of the vehicle registration	
X29	Price of the electrical installation at home.	
G1	Monthly credit to pay	G1 = (X5* X9 /12*(1+ X9 /12)^ X6) / (((1+ X9 /12)^ X6)-1)
X9	TEG is the interest rate on the credit. Its calculation has been standardized in Europe. [http://fr.wikipedia.org/wiki/Taux_effectif_global - cite_note-1](http://fr.wikipedia.org/wiki/Taux_effectif_global#cite_note-1)	
F2	The costs of use of electric vehicles associated with the consumption of energy can be calculated using the variables listed below.	F2 = ((X10*(1+ X27))*X11/100)*Y2+ X12*(1+X27) + X13
Y1	Number of months of vehicle use	
Y2	Estimated number of km traveled per month.	
X10	Price of a kwh of electricity.	
X27	VAT on the price of a kwh of electricity.	
X11	Estimation of the number of kwh consumed over 100km traveled (kWh/100km).	
X12	Battery monthly rent.	
X13	Electricity supplier subscription.	
F4	Different fees per month. The variables are explained below.	F4 = X14+X15+X16+X17 +X18+X19+X20+X21+X22
X14	Vehicle insurance (per month).	
X15	Maintenance per month.	
X16	Technical control (reduced to one month).	
X17	Infractions per month.	
X18	Cleaning per month.	
X19	Parking per month.	
X20	Toll per month.	
X21	Monthly vehicle tax.	
X22	Monthly subscription (Internet- NAV, ...).	
F5	Estimation of the residual value after Y1 months of use.	F5= F1 – (((F1 – Y5)/Y4)/12)*Y1
Y4	Number of years required (wished) for the vehicle usage	
Y5	Residual value (resale) estimated	
F3	To calculate the cost related to the consumption of energy (for an ICEV), we must have an estimation of the fuel consumption (l/100) and fuel prices.	F3 = (X23*(X24*(1 + X28))/100)*Y2
X23	Estimation of the number of liters consumed on 100km traveled (l/100km).	
X24	Net price of a liter of fuel.	
X28	VAT on the price of a liter of fuel.	
G2	Malus on CO2	G2 = X25*(G3/100)
X25	Tax per 100 kg of CO2	
G3	Represents the mass of CO2 emitted by the vehicle (in Kg).	G3 = (X26*X23*Y3)/100

Y3	Estimated emissions of CO_2 (kg) per liter of fuel burned[2].	➢ **2.28 kg for gasoline** ➢ **1.66 kg for GPL** ➢ **2,6 kg for diesel**
X26	Parameter set by the agency that introduced the CO_2 penalty. (For example, average distance traveled by the vehicle). NB. To calculate the CO_2 emissions during Y1 month, just put X26 = Y1 * Y2	
X27	Cost of the battery exchange.	

Player Variables and Constraints. Table 5 provides an overview of the entities taken into consideration in the formulation of the optimization problem as a game. We associate the variables listed in table 4 to each entity that has an economic interest or role in the game. Each entity is also constrained by concerns of profitability (the values it is willing to accept for its variables). Some examples of constraints are shown in table 5.

Table 5. List of variables and constraints per actor (player).

Player	Variables of the player (see table 4 for definitions)	Constraints for the players
EVs producers	X1 X4 X11 X12	These two actors must take into account the investment and production costs, logistics and VAT, economies of scale,…
ICEVs producers	X23 X4	
Electricity supplier	X10 X29 X13	Both of these actors must consider the cost of energy (electricity or fuel) it offers, but also the costs of exploiting the charge stations. Another important constraint is the tax, very significant in the sale price in France,…
Fuel supplier	X24	
Governments, communities and local authorities	X2 X3 X8 X17 X21 X25 X26 X27 X28	Ecological constraints, the overall energy policy, policies related to transportation and employment,…
Road infrastructure companies	X20 X27	Concern for profitability, the importance of investment and return on investment required, costs of road maintenance, ...
Telecommunication operator	X22	Profitability, the amount of traffic data to process, security and data availability in real-time, ...
Insurance companies	X14	Both players are also constrained by profitability objectives. Risk management is very important,…
Bank	X5 X6	

[2] Taken from http://www.carte-grise.org/explication_calcul_bilan_co2.htm - June 2012

	X7 X9	
Parking companies	X19	Profitability objectives, scalability of parking facilities,…
Maintenance and technical control companies	X15 X16 X18	Profitability objectives, initial investment on installations,…
Customers	EV_TCO ICEV_TCO	The constraints on this actor are numerous. The availability of his car, comfort, availability of energy supply, residual value (important as long as he prefers a vehicle that depreciates slowly),…

Player Strategies and Gain Functions. In the following, we will give some examples of player strategies. It is clear that the list in table 7 is not exhaustive, but it is useful and sufficient to illustrate our approach. We will look only at a few players around the EV to simplify the example. Indeed, the objective is to show how we can use game theory in order to propose an EV, with a TCO equivalent (or lower) to that of an ICEV, while underlining the importance of economies of scale.

The choice of strategies for a player can be made by combining his variables. Gains are calculated by deducting expenses from revenues. Tables 6 and 7 provide a summary of gains and strategies for every player in the case of the EV. For the demonstration purpose, we simplify the example focusing only on four players (EV manufacturers, Electricity supplier, Governments, communities and local authorities and Customers) sufficient to understand the rest of the example. Then, in table 6, we underline only the calculation of the gains of these four players.

Table 6. Revenues, expenses and gains of the players.

The player	*Revenues*	*Expenses*	*Gains*
EV manufacturers	RP=X11-X4+X12*Y1	CP= EV production cost	*RP-CP*
Electricity supplier	RF=X29+X13*Y1+X10*X11*Y2*Y1/100	CF=crkwh*X11*Y2*Y1/100) Where crkwh is the production cost of 1 kwh	*RF-CF*
Governments, communities and local authorities	RE=(X2*RP+(X10*X11*Y1*Y1/100)*X27+ X8+X17*Y1+X21*Y1)-X3	CE	*RE-CE*
Road infrastructure companies	RI=X20*Y1		
Telecommunication operator	RT=X22*Y1		
Insurance companies	RA=X14*Y1		
Bank	RB=X7-X5+G1*X6		
Parking companies	RK=X19*Y1		
Maintenance and technical control companies	RM=(X15+X16+X18)*Y1		
Customers	*RC=Residual value of the EV (+ the utility*	*CC=EV_TCO*	*RC-CC*

	of using the vehicle)		

Table 7. Examples of strategies.

Player	Description of some strategies
EV manufacturers	• Rent the vehicle. • Rent the battery and sell the vehicle. • Sell the vehicle (including battery). • Integrate Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) to provide electric energy • Integrate fast charging / normal charging / quick battery exchange.
Electricity supplier	• The price of electricity (peak versus off-peak hours, different countries). • Propose a preferential cost of electricity. • Support fast charging / normal charging / quick battery exchange. • Provide home installation for charging. • Integrate V2H and V2G to buy electricity from vehicles.
Government and local authorities	• Offer technical controls, offer installation certifications • Zero-rate (or reduced the tax) on the electrical energy supplied to charging stations or private homes • Provide environmental bonus for purchasing an EV • Provide other incentives (e.g. reduce car taxes or offer costs of vehicle registration).
Road infrastructure companies	• Reduce the toll fees. • Install battery exchange stations and sell the service.
Telecommunication operator	• Develop (or not) communication protocols or sell services dedicated to vehicle communications.
Insurance companies	• Provide (or not) specific offers for electric vehicles.
Bank	• Provide (or not) specific advantages for electric vehicles.
Parking companies	• Install (or not) battery exchange stations and sell the service.
Maintenance and technical control companies	• Present (or not) attractive offers for electric vehicles.

Of course, one can imagine many other possible strategies:

- Propose a leasing contract for a certain duration given a decreasing rate (over 5 years for example). In the case of Vehicle-to-Home (V2H) and / or Vehicle-to-Grid (V2G), how much would V2H or V2G energy cost? Will it be taxed?
- Sell information to (or buy it from) telecommunications operators (e.g. driving profiles, road types, time spent in traffic jams).
- Integrate connectivity services in the rent fees and have an architecture and standard communications protocol, etc.

The concept of interdependence between strategies, therefore between stakeholders or players, can be explained briefly using the example of V2G. The decision to implement the V2G service does not depend only on the vehicle manufacturer but also on the energy supplier: the vehicle manufacturer will not propose vehicles integrating V2G service if no energy supplier is willing to buy the electric energy transferred from the vehicle to the grid. This same decision depends also on the strategies of authorities that may impose taxes on the electric energy "sold" to the grid or laws constraining the choices of technical solutions and so on. In addition, will the customer accept this service? Does he accept to install a smart meter in his house that might record and share his consumption habits or profile to other parties? The authorities have to regulate this service, will they tax energy sold? What will be the scheme followed by different countries?

Mathematical Formulation. In order to illustrate our approach and limit the number of pages of this paper, we will only present some examples of player strategies.

Let us define the EVEcosys (Electric Vehicle in its Ecosystem) as a non-cooperative game with 4 players: the EV manufacturer, Government and Local Authorities, the Energy Supplier and the Customer, respectively **{P, G, E, C}**. Each player has a set of strategies, respectively **{SP, SG, SE, SC}. SP = {SP1, SP2, SP3}, SG = {SG1, SG2}, SE = {SE1, SE2}, SC = {SC1, SC2, SC3}.**

Π = (ΠP, ΠG, ΠE, ΠC) is the outcome of the game (or gain function) where **ΠP (SP1, SG1, SE1, SC1)** is the gain of player **P** when strategies **(SP1, SG1, SE1, SC1)** are chosen.

For the implementation of our example, we use the player strategies shown in table 8.

Table 8. Examples of strategies per player used in our example.

Player		Strategies	
P	EV manufacturer	SP1	Rent EVs during 5 years.
		SP2	Sell EVs (including the battery)
		SP3	Sell EVs and rent batteries.
G	Governments and local authorities[3]	SG1	Purchasing bonus (5 000 Euros for example).
		SG2	No purchasing bonus.
E	Energy supplier	SE1	Standard cost of energy (kWh) and charge for installing charging stations
		SE2	Preferential cost of energy (kWh) and free installation of charge stations
C	Customer	SC1	Buy nbr1 EVs
		SC2	Buy nbr2 EVs
		SC3	Buy nbr3 EVs

Where nbr1, nbr2, nbr3 represent the expected number of vehicles purchased by customers given the strategies of the other 3 players. We should, however, add the probabilities of economies of scale (given by the strategy of the customer) to find the mixed-strategy equilibrium using the probabilities presented in the following table.

Table 9. Mixed strategies per player.

Strategy	SP1	SP2	SP3	SG1	SG2	SE1	SE2	SC1	SC2	SC3
Probability	PP1	PP2	PP3 = 1-PP1-PP2	PG1	PG2 = 1-PG1	PE1	PE2 = 1- PE1	PC1	PC2	PC3 = 1-PC1-PC2

Tests and Results. Let us start with an overview on the difference in TCO between an internal combustion engine vehicle (ICEV) and an electric vehicle (EV) after 5 years and the revenue of each player (stakeholder), as shown in figure 4 (this distribution example is for illustration purposes only). In this example, the customer gains are 40785-36536 = 4248 euros (for 5 years).

For the calculation of equilibrium in our example, the use of our model for calculating the TCO and player gains by combining strategies yields the results presented in tables 10 and 11.

[3] Gains of some players may not be directly perceptible. For Authorities, for example, they will gain in the long term by reducing the oil importation and by promoting the consumption of electrical energy.

These are the results of gains after 5 years use of electric vehicles (initialization data are not included in this paper).

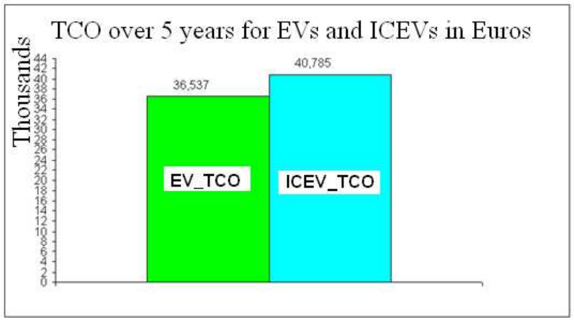

Figure 4. TCO difference between EV and ICEV.

For the calculation of gains of the customers, we deduce the EV_TCO (given the combination of the strategies of other actors) from the ICEV_TCO of the same category.

Take for example the average of ICEV_TCO equal to 40 785 euros. As long as we focus only on the four actors, the ICEV_TCO equals an average of 32,685 euros (because we consider only the costs related to these four actors, excluding other costs related to other stakeholders). Thus we see, for example:

- In the case of strategy combination (SP1, SG1, SE1), the customer earns 4429 euros.
- In the case of strategy combination (SP3, SG2, SE1), the customer loses 1108 euros.

In the case of the combination of (SP1, SG1, SE1), for example, the EV manufacturer earns 5461 euros, the government earns 1104 euros, the energy supplier earns 632 euros and the customer wins 4429 euros. In the case of two combinations (SP3, SG2, SE1) and (SP3, SG2, SE2), the customer does not win: he loses because the EV TCO is higher than the TCO of an ICEV of the same category.

Table 10. Player gains over 5 years in Euros (without customer strategies).

Strategies	ΠP producer gains for EV	ΠG gains of governments and local collectivities	ΠE energy supplier gains	ΠC customers gains
(SP1,SG1,SE1)	5461	1104	632	4429
(SP2,SG1,SE1)	3000	1104	632	6890
(SP3,SG1,SE1)	7200	1902	632	1892
(SP1,SG2,SE1)	5933	4104	632	957
(SP2,SG2,SE1)	3000	4104	632	3890
(SP3,SG2,SE1)	7200	4902	632	-1108
(SP1,SG1,SE2)	5461	1104	412	4649
(SP2,SG1,SE2)	3000	1104	412	7110
(SP3,SG1,SE2)	7200	1902	412	2112
(SP1,SG2,SE2)	5933	4104	412	1177
(SP2,SG2,SE2)	3000	4104	412	4110
(SP3,SG2,SE2)	7200	4902	412	-888

Table 11. Player gains over 5 years in Euros, including customer strategies

Strategies	ΠP producer gains for EV	ΠG gains of governments and local collectivities	ΠE energy supplier gains	ΠC customers gains

(SP1,SG1,SE1,SC1)	546109123,3	110351800	63220000	442877114
(SP2,SG1,SE1,SC1)	300000000	110351800	63220000	688986237,3
(SP3,SG1,SE1,SC1)	720000000	190151800	63220000	189186237,3
(SP1,SG2,SE1,SC1)	593330947,9	410351800	63220000	95655289,35
(SP2,SG2,SE1,SC1)	300000000	410351800	63220000	388986237,3
(SP3,SG2,SE1,SC1)	720000000	490151800	63220000	-110813762,7
(SP1,SG1,SE2,SC1)	546109123,3	110351800	41220000	464877114
(SP2,SG1,SE2,SC1)	300000000	110351800	41220000	710986237,3
(SP3,SG1,SE2,SC1)	720000000	190151800	41220000	211186237,3
(SP1,SG2,SE2,SC1)	593330947,9	410351800	41220000	117655289,4
(SP2,SG2,SE2,SC1)	300000000	410351800	41220000	410986237,3
(SP3,SG2,SE2,SC1)	720000000	490151800	41220000	-88813762,72
(SP1,SG1,SE1,SC2)	764552772,6	154492520	88508000	620027959,6
(SP2,SG1,SE1,SC2)	420000000	154492520	88508000	964580732,2
(SP3,SG1,SE1,SC2)	1008000000	266212520	88508000	264860732,2
(SP1,SG2,SE1,SC2)	830663327,1	574492520	88508000	133917405,1
(SP2,SG2,SE1,SC2)	420000000	574492520	88508000	544580732,2
(SP3,SG2,SE1,SC2)	1008000000	686212520	88508000	-155139267,8
(SP1,SG1,SE2,SC2)	764552772,6	154492520	57708000	650827959,6
(SP2,SG1,SE2,SC2)	420000000	154492520	57708000	995380732,2
(SP3,SG1,SE2,SC2)	1008000000	266212520	57708000	295660732,2
(SP1,SG2,SE2,SC2)	830663327,1	574492520	57708000	164717405,1
(SP2,SG2,SE2,SC2)	420000000	574492520	57708000	575380732,2
(SP3,SG2,SE2,SC2)	1008000000	686212520	57708000	-124339267,8
(SP1,SG1,SE1,SC3)	982996421,9	198633240	113796000	797178805,2
(SP2,SG1,SE1,SC3)	540000000	198633240	113796000	1240175227
(SP3,SG1,SE1,SC3)	1296000000	342273240	113796000	340535227,1
(SP1,SG2,SE1,SC3)	1067995706	738633240	113796000	172179520,8
(SP2,SG2,SE1,SC3)	540000000	738633240	113796000	700175227,1
(SP3,SG2,SE1,SC3)	1296000000	882273240	113796000	-199464772,9
(SP1,SG1,SE2,SC3)	982996421,9	198633240	74196000	836778805,2
(SP2,SG1,SE2,SC3)	540000000	198633240	74196000	1279775227
(SP3,SG1,SE2,SC3)	1296000000	342273240	74196000	380135227,1
(SP1,SG2,SE2,SC3)	1067995706	738633240	74196000	211779520,8
(SP2,SG2,SE2,SC3)	540000000	738633240	74196000	739775227,1
(SP3,SG2,SE2,SC3)	1296000000	882273240	74196000	-159864772,9

The results of simulations using the application GambitSoftware[4] for Nash equilibrium (the gains distribution per player) and mixed strategies over a span of 5 years are shown in tables 12 and 13.

Table 12. Player gains in Nash equilibrium with mixed strategies in Euros.

ΠP: manufacturer gains for EV	ΠG: government and local authorities gain	ΠE: energy supplier gains	ΠC: customers gains
720000000	490151800	63220000	-110813762

[4] http://www.gambit-project.org/doc/index.html (November 2012)

Table 13. List of probabilities per strategy.

Strategy	SP1	SP2	SP3	SG1	SG2	SE1	SE2	SC1	SC2	SC3
Probability	0	0	1	0	1	1	0	1	0	0

The results of this example give Nash equilibrium in pure strategies. An equilibrium is reached when combining strategies (SP3, SG2, SE1, SC1) with the gains for the manufacturer, the government, the energy supplier and the customer equal to (720000000, 490151800, 63220000, -110813762) respectively. This means that the manufacturer will choose to sell the EV and rent only the battery, the energy supplier will offer a standard cost of a kwh and will not offer electrical installation and the government will not support the purchase, therefore the customers project to buy only100000 EVs in this case.

Indeed, it is an equilibrium with dominant strategies. The manufacturer of EVs is sure to get as much as possible when playing SP3 rather than SP1 or SP2, whatever the choices of the other actors. Similarly, the government wins the maximum when there is no bonus for the purchase (at least in the short term, ecological consideration notwithstanding). The energy supplier also has a higher profit in the case of no preferential energy prices and facilities. The customer is the loser in this combination of strategies knowing that the EV will cost more than a combustion engine vehicle of the same category. This is because there is no incentive to buy EVs despite the fact that significant economies of scale will arrange some actors. Indeed, to achieve economies of larger scale, players must choose other strategies. If the four players (Manufacturer, Government, Energy Supplier and Customer) play their respective strategies (SP3, SG1, SE1, SC3), they earn respectively 982996421, 198633240, 113796000, 797178805 significantly more than the gains in an equilibrium for all players except for the Government. Can the Government play its dominated strategy? The answer to this question is not easy and will be different for different countries. The interest of promoting EVs depends certainly on other factors related to more global energy and environmental policies.

However, the results show that despite the possibility that some actors can play strategies less favorable at the beginning (the case of bonus given by the Government), the equilibrium is reached thanks to the combination of strategies (SP3, SG2, SE1, SCx). Thus, we must consider this information well in advance to anticipate EVs market and take into account the cost constraints. Note also that the input data used in this example in terms of energy costs (electric vs. fossil), even if they are approximate, they reflect the average of current prices. They may however change in the future, in scenarios of, for example climate policy and international tensions over oil prices, which would mean that the curve of downward trend in the evolution of EV_TCO would cross the curve of increasing ICV_TCO. A conclusion, among others, that came from CIRED5.

Finally, it is clear that it is crucial to validate a posteriori the results in light of new, more realistic data and the likelihood of their evolution over time, collected through market studies and taking into account all stakeholders. The objective of this small example is to show the design approach and the usefulness of the architectural equilibrium.

It is indeed necessary to have the right information to make the right decisions. Modeling as a game is helpful in order to accumulate knowledge and know-how through future scenario analysis, especially for the exploration of both business models and technical solutions. This way of reasoning helps to manage the diversity of optimized solutions. The purpose is to arrive quickly to the development of new systems by reusing existing designs. Research and analysis studies on industry and economy trends, as performed by many specialized organizations, could provide valuable insight for this. Herbert A. Simon stated the concept of bounded rationality (*the notion that the rationality of individuals in making decision is limited by the*

5 CIRED: Centre International de Recherche sur l’Environnement et le Développement, http://www.centre-cired.fr/

information they have and the finite amount of time they have to make decisions (cf. (de Weck et al., 2011))). Also, Carveth Read quoted: "It’s better to be vaguely right than exactly wrong." (cf. (Caseau, 2012)).

Discussion and Perspectives

Negotiation between stakeholders - A cooperative game? It is also possible to consider the game as cooperative in the sense that players can agree on their respective strategies to play. The cooperative games can illustrate possible cooperation as part of broader strategies. This way of “doing business” may however be limited by antitrust laws in certain countries. In this type of cooperation, the concept of interdependence is clearly significant in the sense that players can clearly see the interest to cooperate. One can imagine, for example, some kind of cooperation between the vehicle manufacturer and the telecommunications operator to reduce service costs associated to the communication of the vehicle to the internet. The vehicles manufacturer wins by offering a relatively inexpensive service, while the telecommunications operator wins by economies of scale and customer loyalty.

However, this type of cooperation can negatively impact a player if he has not studied his own strategy with regards to those of other players. In this small example of cooperation, it is possible that customers might prefer another telecommunications operator that can influence differently the decisions of the vehicles manufacturer.

Impact of architectural equilibrium on the choice of architectures. Logically, the choice of architectural equilibrium has an impact on the design of the SOI. This choice gives the first guidelines for choices made throughout the design of the system. It guarantees both stability of the environment after the integration of the new system and the viability of the latter (economic viability for example).

The example of the electric vehicle can be instructive. For instance, suppose that suppliers of electric power in a given country, after consulting with the EV manufacturers, decide that fast charging systems will not be installed. EV manufacturers should consider this design constraint at the architectural level, on (at least) the external interfaces of the system. Thus, we can finally say that the definition of good external interfaces necessitates the definition of architectural equilibrium.

One major difficulty is to determine *a priori* all emergent behaviors in a reliable way with an equilibrium in mixed strategies. Indeed, there is no strict incentive to play the equilibrium strategy and the use of mixed strategies implies the use of assumptions of expected utility and assumptions about the aversion to risk (Koessler, 2008). Another difficulty in solving games is the completeness of available information. It is not easy for a player to know all the strategies of other players without some kind of cooperation agreements often prohibited by antitrust laws. Additionally, sometimes it is very difficult to formalize the gain functions (take for instance the brand image) where the notion of customer perception is important. One can also consider the probable emergence of unforeseen issues that lead clearly to situations of decision making under uncertainty.

However, architectural equilibrium research can also contribute effectively in advanced industrial research projects. Indeed, in this type of projects where system design begins almost from scratch, the knowledge of all stakeholders around the system of interest during its life cycle, while being of paramount importance, is not easy. For each of these stakeholders, understanding their expectations, mainly from a strategic point of view, helps greatly in the definition of the system we want to design and implement in order to sustainably integrate it in its environment. This step serves as a solid basis for the definition of the problem we want to solve (system missions, ...) and it is only from there that we can start the search for solutions.

In this type of innovative system, it is useful to consider first the construction of the environment that is often not stable, a priori. Value creation is an integrative process of multiple stakeholders. Long term cooperation give / give, win / win and economies of scale are important. Before attempting to share a "new" market, we must first create it.

In this paper, we presented the contribution of game theory to research architectural equilibrium in the context of complex systems engineering. Our approach based on the use of an architectural design framework and optimization models also takes into account the type of decision being made. For interdependent decisions between stakeholders in the lifecycle of a given system, the concept of equilibrium is important. Architectural equilibrium of a SOI guarantees its integration in its environment, the stability of this environment and the satisfaction of all stakeholders. This assertion is shown using a practical example related to electric vehicles. Many elements are likely to contribute to their success, and do not necessarily depend on automakers, but also on other stakeholders. Hence, in the context of EVs, the problem for car manufacturers is not far from being a system-of-systems type of problem, regarding complexity and the need to analyze these systems form higher point of view and to design them using more rigorous approaches.

The approach we presented is an integration of several processes: systems architectural design, multi-objective optimization and equilibrium in the sense of game theory. It allows the reduction of engineering costs and time through the reuse of models, and reducing the time to market as a consequence. Indeed, the approach can serve as a baseline for managing variability and uncertainty. This improves the adaptability of technical solutions by allowing to anticipate other contexts of use and associated business models.

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Biography

Abdelkrim Doufene has got a PhD (2013) from Ecole Polytechnique (France). He is a research engineer working for the automotive manufacturer Renault and a teaching assistant at Paris 1 University Panthéon Sorbonne (France) . His research topic is in the domain of complex systems architecture, applied to the design of electric vehicles (zero emissions of greenhouse gases). His research includes developing applications of multiobjective optimization modeling and game theory in the context of complex systems engineering. He possesses a master degree in "Information and Decision Systems" delivered by "Université Paris 1 Panthéon Sorbonne", ESSEC and CNAM (France). He is also “information systems engineer" graduate from “Ecole Nationale Supérieure d’Informatique” (Algeria).

Dr. **Hugo Guillermo Chalé Góngora** is a System Architect for R&D projects dealing with system of systems and autonomous vehicles at Renault. For the last several years, he has been in charge of developing and deploying Systems Engineering and MBSE for the engineering divisions of Renault. Dr. Chalé is actively promoting the INCOSE Automotive Interest Group initiative.

Former student of Ecole Normale Supérieure, **Daniel Krob** got a Ph.D. (1988) and an Habilitation (1991) in Computer Science from University Paris 7. He is presently Senior Researcher at the French National Center for Scientific Research (CNRS), institute professor at Ecole Polytechnique and head of the Thales chair "Engineering of Complex Systems" since its creation in 2003. Daniel Krob worked in algebraic & enumerative combinatory, algorithms for mobile telecommunications and finite automata & formal languages, before specializing nowadays in systems architecture, systems engineering and systems modeling. He is the author of more than 90 scientific papers, 4 books and holds 2 patents. Daniel Krob founded and directed the "Laboratoire d’Informatique Algorithmique: Fondements et Applications" (LIAFA) of University Paris 7 during 6 years. He was also head, during several years, of the steering committees of two major international conferences in combinatorics & theoretical computer science (FPSAC & STACS). Presently Daniel Krob is chairman of the evaluation commitees of the "Information Management & Modelling" departement of the French Aerospace lab (ONERA) and of the "Architecture & Evaluation of Systems of Systems" group of the technical expertise department of the French ministry of defense (DGA). At international level, he is also one of the 15 founding members of the Omega-Alpha honour association in Systems Engineering.