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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

1. Introduction & Context
2. Why Systems Architecture and Multidisciplinary / Multi-Objective Optimization
3. Why Game Theory ?
4. Application to Electric Vehicles in their ecosystem
5. Conclusions & Perspectives

01 Introduction & Context

Introduction / Context

- ✓ Engineering of complex industrial systems with a holistic approach.
- ✓ Taking into account the whole life cycle of systems.
- ✓ Supporting tradeoff analysis and decision making.

But

- ➢ *Several multidisciplinary objectives and constraints.*
- ➢ *Conducting analyzes, defining the right criteria and evaluating alternatives are difficult tasks.*
- ➢ *The separation between the problem definition and solution design is often blurry.*

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Main purpose

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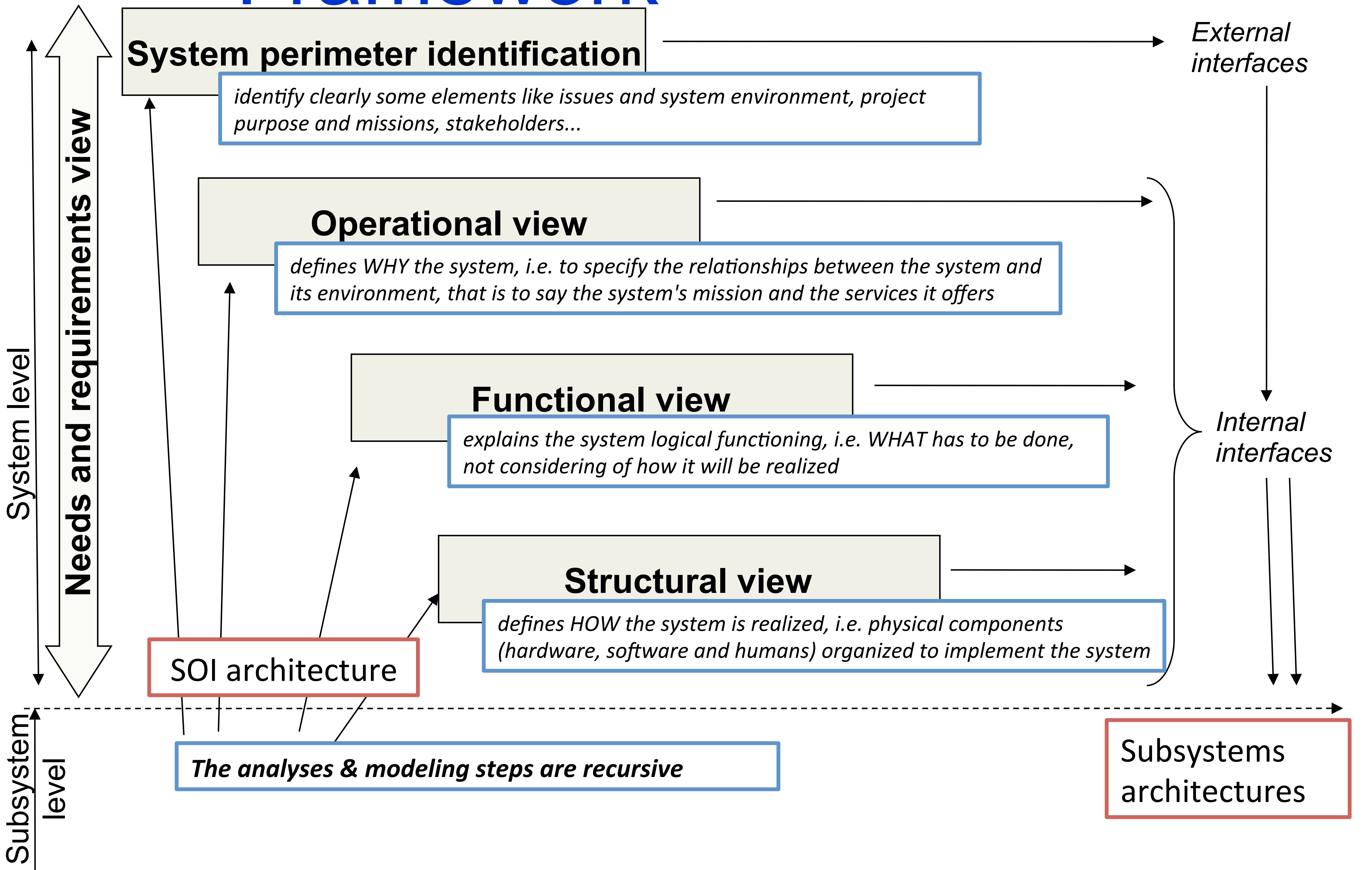
- Bridge the gap between problem definition & solution design.
- Clarify the link between design constraints and design variables.
- Structure and organize the architectures of the SOI
  - Covering all the scope of the system architecture & the different abstraction levels.
- Support trade-off analysis and decision making.
- Find optimal solutions and ensure a stable integration of the SOI in its environment.

02 Systems Architecture and Multidisciplinary / Multi-Objective Optimization (MOO)

Architectural Design Framework



MOO problem mathematical formulation

$$\min \mathbf{J}(\mathbf{x},\mathbf{p})$$

$$\text{s.t.} \quad \mathbf{g}(\mathbf{x},\mathbf{p}) \le 0$$

$$\mathbf{h}(\mathbf{x},\mathbf{p}) = 0$$

$$x_{i,LB} \le x_i \le x_{i,UB} \quad (i = 1, \ldots, n)$$

$$\mathbf{x} \in S$$

where

$$\mathbf{J} = \left[J_1(\mathbf{x}) \quad \cdots \quad J_z(\mathbf{x}) \right]^T$$

$$\mathbf{x} = \left[x_1 \quad \cdots \quad x_i \quad \cdots \quad x_n \right]^T$$

$$\mathbf{g} = \left[g_1(\mathbf{x}) \cdots g_{m_1}(\mathbf{x}) \right]^T$$

$$\mathbf{h} = \left[h_1(\mathbf{x}) \cdots h_{m_2}(\mathbf{x}) \right]^T$$

MOO problem resolution

- Preference and priority between optimization objectives influence the choice of solving methods.
- Methods with **a priori** or **a posteriori** articulation of preferences.
- The objective is NOT to find one solution but several alternatives… The predominant concept in defining an optimal point is that of Pareto optimality - (with a posteriori articulation of preferences).
- In the case where preferences depend on several **interdependent** stakeholders or decision makers, the concept of **equilibrium** is important.

Example– electric vehicles

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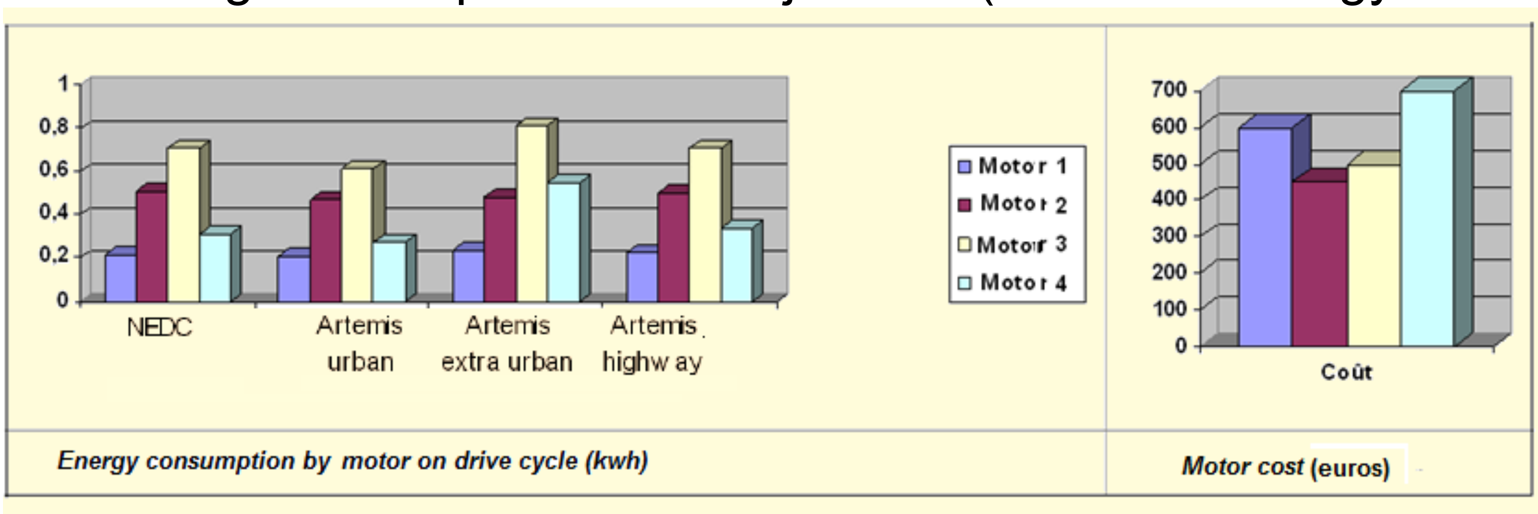
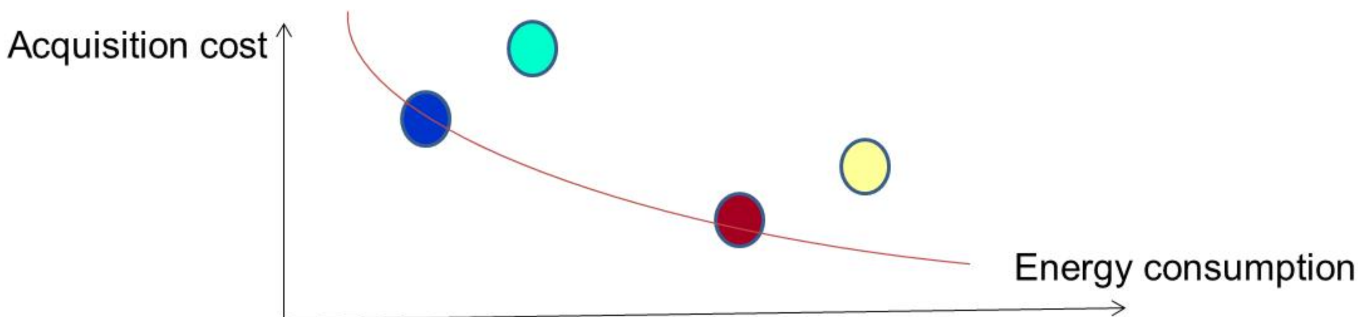
Results - Pareto Frontier

Example: choice of an electric motor for the electric vehicle powertrain, according to two optimization objectives (TCO and Energy Consumption)





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03 Why Game Theory ?

Interdependence

1 - Multidisciplinary and multi-objective optimization models, with a posteriori articulation of preferences (using Pareto frontiers) are useful for searching the best architectures given several constraints and needs during the whole life cycle of the SOI.

→ Support of "independent" decisions

2 - Equilibrium models, in the sense of game theory, serve to searching the best architectural equilibrium to satisfy different stakeholders around a SOI and ensure the stability of the environment on the long term.

→ Support of "interdependent" decisions

Game theory link with SE

Mathematical formalization

- A game with ***n*** players. — Stakeholders
- Each player ***i*** has a set of ***Si*** strategies. — Needs, constraints
- Total gain. — TCO, Lifecycle
- ***s=(s1,…,sn)*** is a combination of strategies of ***n*** player where ***s_i*** is the strategy chosen by the player ***i.*** — Tradeoffs
- ***Π = (Π1,…,Πn)*** is the result of the game where ***Πi(s1, …,sn)*** is the gain of the player ***i*** when ***s*** is chosen.. — Solution

Equilibrium

An equilibrium situation can be seen as a "win-win" solution, in which a given player does not have an interest in changing his own strategy (given the strategies chosen by the other players)

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Generic Approach

1. Analysis of the environment of the SOI.
2. Identification of stakeholders (Players)
3. Analysis of stakeholder needs and identification of measures of effectiveness (Focus on their business strategies and most important constraints)
4. Identification and formalization of the interdependence of strategies.
5. Analysis of the SOI life cycle and its Total Cost of Ownership (TCO).
6. Formalization of the game, with the TCO being the total gain.
7. Definition of distribution scenarios
8. Search of architectural equilibrium (using Nash equilibrium).
9. If coalitions are acceptable, imagine coalitions between stakeholders – Go to 7
10. Implement the equilibrium solutions

04 Application to Electric Vehicles in their Ecosystem

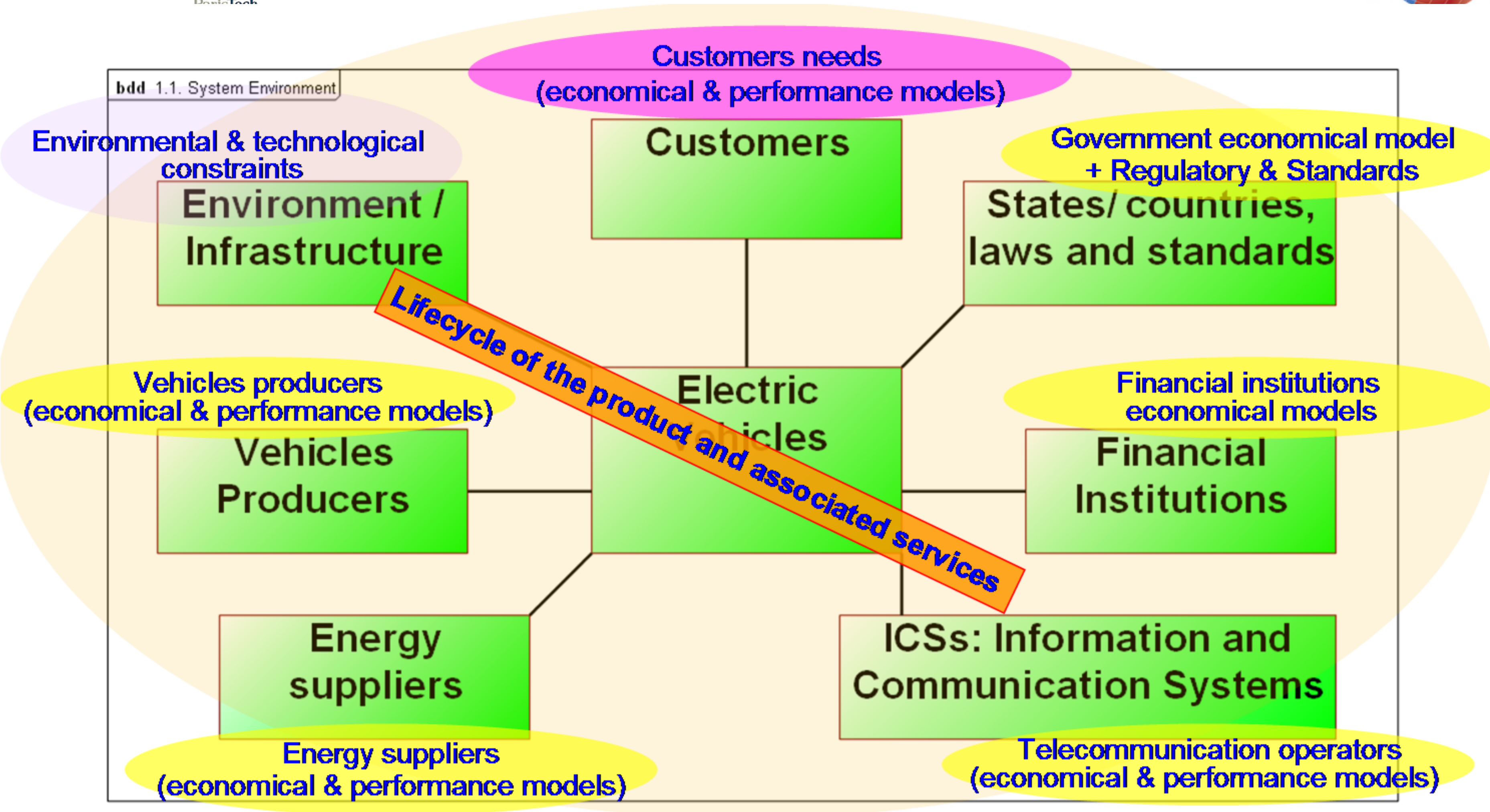
Why Electric Vehicles?

- **Huge economic and environmental stakes**
  - 1.6 billion vehicles worldwide in 2030 → 2.5 billion in 2050 (EC).
  - High differences in density* of vehicles in the world (WorldBank, 2012).
  - Energy consumption by road transportation represents about 20% of total consumption [EEE, 2010], [EET, 2007].
  - Internal combustion vehicles are responsible for about 10% of CO_2 emissions in the atmosphere (www.wri.org).

- **A complex environment**
  - Interests, stakeholders, stakes… and thus, **equilibrium**, will depend on many different PESTEL** contexts

* Number of vehicles per 1000 inhabitants.
** PESTEL for Political, Economic, Social, Technological , Environmental and Legal

Environment / Players



+ Equilibrium model

Data input

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1- List of variables and relations

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	

2 - Allocation of variables per player

Player	Variables of the p
EVs producers	X1 X4 X11 X12
Electricity supplier	X10 X29 X13
Governments	X2

3- Examples of strategies per player

	Player	Strategies	
P	EV manufacturer	SP1	Rent EVs
		SP2	Sell EVs
		SP3	Sell EVs
G	Governments and local authorities[3]	SG1	Purchasi
		SG2	No purch
E	Energy supplier	SE1	Standard charging
		SE2	Preferent charge st

4- Gains calculation according to the strategies combination

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 prod cost of 1 kwh	[illegible]
Governments, communities and local authorities	RE=(X2*RP+(X10*X11*Y1*Y1/100)*X27+ X8+X17*Y1+X21*Y1)-X3	CE	R

Examples of results

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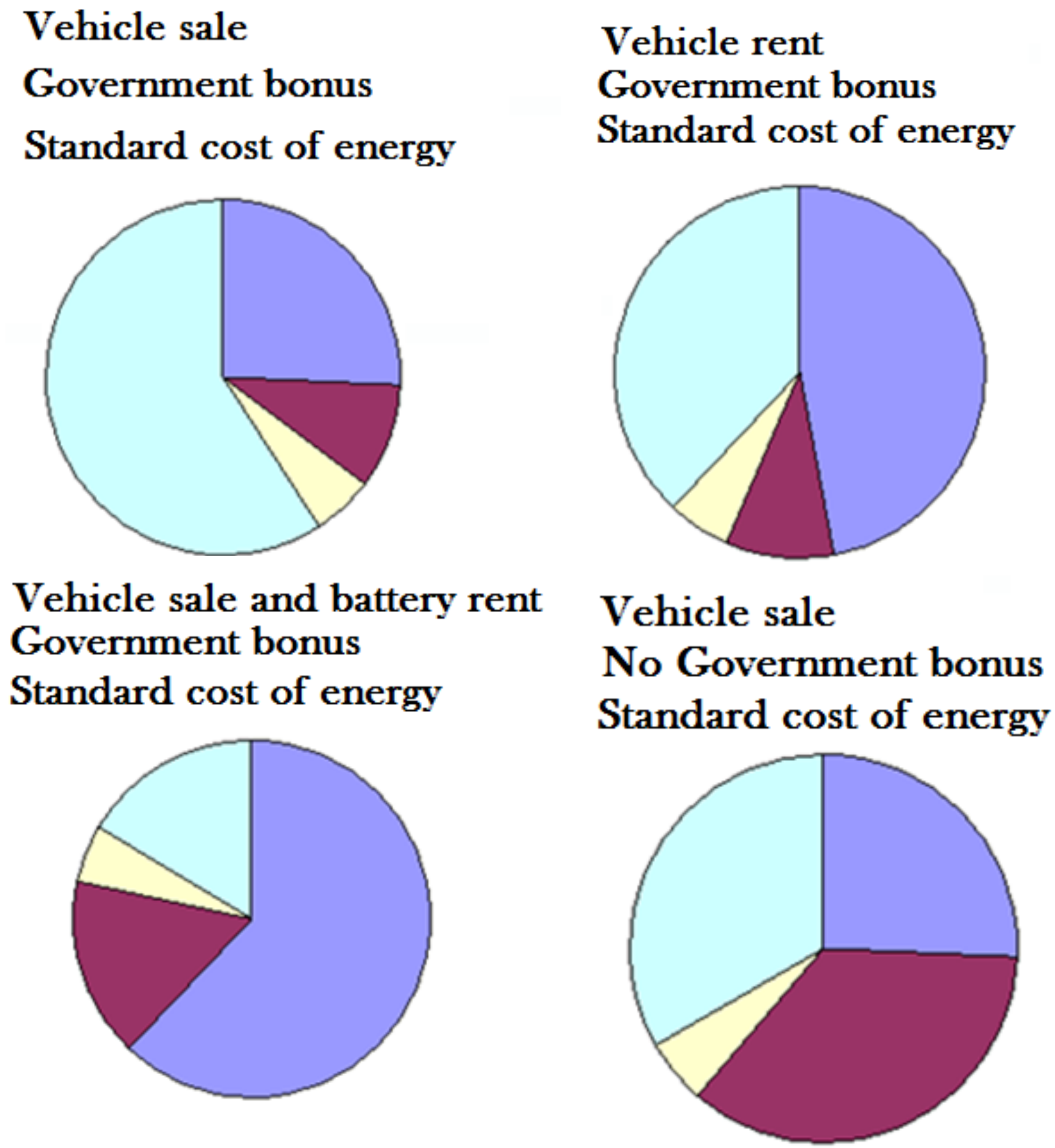
Example of scenarios of gains sharing by combining strategies (for one vehicle)



- EV producers
- Governments
- Energy suppliers
- Customers

Discussion

- In our example, we reached an equilibrium where the economy of scale did not play an important role

- In order to increase gains some players have to « make concessions », but…

  - Who will be willing to play a **dominated strategy** in order to reach a greater economy of scale?

  - When will the game stabilize?

  - Can the players build coalitions?

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05 Conclusions & Perspectives

Conclusion

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- We presented an integrated approach combining systems engineering, multi-objective optimization and equilibrium in the sense of game theory.

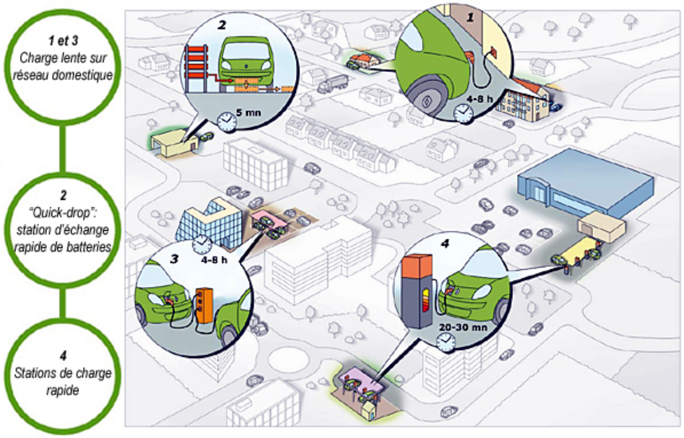
- The resulting models can serve as a baseline for
  - Managing variability and uncertainty.
  - Adapting the technical design to different contexts of use and associated business models.
    - Reducing engineering costs by reusing models.
    - Reducing time to market.

Conclusion

- In a complex and increasingly uncertain environment, what is considered as reliable now might not be so tomorrow!
- Value must be created ***before*** it can be shared
  - Give / Give - Win / Win situations.
  - Importance of long-term and economy of scale (i.e. taking into account the whole system lifecycle)
- Game theory looks very promising to study architectural equilibrium and to analyze interdependent decisions.
  - This contribute to ensure a better integration of the SOI, the stability of its environment and the satisfaction of all stakeholders in the long-term

Thank you for your attention

Any Questions?



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