INTELLECTUAL PROPERTY AND EVOLUTION OF THE COMPLEX NATURE OF ELECTRICAL VEHICLES.

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ABSTRACT

Following new institutional economics (Ostrom, 2005) and complex systems (Holland, 2006), we identify the tragedy of the anti-commons (Heller, 2008) and patent thicket (Shapiro, 2001) in electric vehicles from an analysis of patent´s technological clases (USPTO, 1976–2012). Using network theory (Watts, 1999), we describe the evolution of electric vehicle technology, which has grown from a relatively disconnected network to a hierarchically connected network in which the system is organized into subsystems by a process of integration /modularization (Baldwin & Clark 1999). We confirm the electric vehicle´s technological complexity and the patent thicket relationship.
Keywords: electric vehicle; technologies, patents thickets, integral design, modular design, tragedy of the anti-commons, networks.

INTRODUCTION

The institutional theory of collective action (Ostrom, 1990; 2005 and Poteete et al., 2011) entails difficulties with the administration of traditional common pool resources (such as water, forests, land) (Heller, 2008); one of these is related to knowledge.[1] If the knowledge and the intelectual property required to develop a good or technology is fragmented among many rival agents who block its use or exploitation, then the result can be underusage of the good[2], leading to the "tragedy of the anti-commons" (Heller, 1998)[3]. Like the concept of the tragedy of the commons, the tragedy of the anti-commons is also motivating empirical work, the construction of formal models and refinement of institutional economic theory.

Although electric vehicles are complex goods that involve a suite of complementary technologies, there are no studies of this problem in the automotive industry. The purpose of this paper, then, is to reconstruct and explain the evolution of the complex technological nature of electric vehicles and the relationship between this configuration and the fragmentation of rights to intellectual property among multiple agents. The story of electrical vehicle technology is compiled from relevant patents registered with the United States Patent and Trademark Office between 1976 and 2012.[4] The central questions are: How can the theory of complex systems be employed to identify the existence and evolution of a dense

[1] Ostrom (1990) recognizes "knowledge" as a key element that affects collective action: "common knowledge" of the collective problem enables participants to reach agreements. Moreover, there are different types and levels of information between players.

[2] While the tragedy of the commons plays out in the depletion of the resource (Ostrom, 1990).

[3] To reconstruct and explain how the social dilemma arises, it is useful to study the nature of a good, the structure of the situation of action, and the characteristics of the participants (Ostrom, 2005).

[4] 2358 patents related to the development of electric vehicles were obtained from the patent database of the United States Patent and Trademark Office (USPTO). See note 13.

network of technological knowledge, intelectual property and agents in the development of electric vehicles? To what extent does the evolution of the nature of the good (electric vehicles) explain the existence of overlapping property rights and the tragedy of the anti-commons?

This study is organized as follows: the first part discusses the nature of knowledge and explains to what extent fragmentation of knowledge and of the associated intellectual property can lead to problems of underutilization. The second part describes how the complexity of a good evolves from its architecture (modular/integrated). The third section gives an overview, based on the relevant patents, of the invention of electric vehicles, introducing the concept of technological classes as an input to describe the system. Based on this and the theory of complex systems, the fourth part explains how technological invention in electric vehicles changed from being a network of small disconnected pieces of knowledge to a network of complex, extensive, hierarchical knowledge. In the fifth section, evidence is presented that knowledge is fragmented mainly in highly connected areas where rival businesses are located. With this, the presence of the patent thicket and an anti-commons scenario are identified in the process of invention of electric vehicles.

1. - KNOWLEDGE, PATENT THICKET AND ANTI-COMMONS

Following Hess and Ostrom (2003), in this study, data, information and knowledge are all considered to be knowledge. That is, data are a part of information, and the organization and use of information is knowledge. If we consider knowledge as a resource, we might ask what sort of resource it is. The answer is that, depending on its nature and what institutional arrangement it is held under, knowledge may be a public, common, club, or private good.[5]

There are two important aspects of the nature of knowledge. Knowledge is an intangible asset, but it exists to the extent that there is a physical medium holding it; for example, a person's memory, a book, an electronic database, or a community (Hess and Ostrom, 2003; Heller, 2008). The way in which it is held determines the possibility or impossibility of extracting it as a good, and to what degree.[6] The institutional arrangement is also determined by the nature of the good, and this is especially important in the case of intellectual property rights[7]. The laws of property create artificial forms of exclusion (Coriat, 2011). For example, a technology may be easily accessed in the patent database and relatively easy to recreate, but impossible to develop or exploit (at least legally) if the rights holder refuses to grant a license to exploit the knowledge[8].

These two aspects of knowledge illuminate key dimensions of inventive capacity in the electric vehicle sector. In the innovation of complex products such as the electric vehicle, no single person or company can develop the product; rather, it requires a large population of highly specialized agents. Therefore, since knowledge and intellectual property are associated, the components required to develop a piece of complex technology are scattered and fragmented across different complementary patents (patent thicket). Any agent holding a portion of the knowledge could refuse to grant the license to use it (the retention problem) and thus block innovation or increase the cost. The result: underutilization of the good or the tragedy of the anticommons (Heller, 2008).

[5] See Ostrom's Figure 1.1, 2005: 9.

[6] For example, in a library (resource system), the use of a print book by one person prevents another from using it simultaneously (sustractability).

[7] As another example, a technological invention – which is knowledge – is relatively easy to protect legally by means of intelectual property rights, but a language, which is also knowledge, is in the public domain.

[8] Digital technology has made ways of holding knowledge increasingly cheaper and easier to duplicate, with the result that both rivalry and the ability to exclude have been reduced.

At the core of the anti-commons problem is a network of owners of complementary patents or a patent thicket, which can be caused by three factors: the complexity of the good (IPO, 2011), the strategy of some participant (Bessen *et al*., 2012; Cockburn *et al.*, 2010), or bureaucratic roadblocks in different patent offices (Bessen and Meurer, 2008). In the present study, we limit our analysis to the first cause[9]. For this purpose, we will begin by seeking to answer the question: How can the evolution of the architecture of a complex technological system such as that of electric vehicles be represented and analyzed?

2. - COMPLEXITY, INTEGRATED SYSTEMS AND MODULAR SYSTEMS

In the theory of technological innovation, there are two different architectures that represent the ways components and functions interact from a spatial and functional point of view. In industry – in the automobile industry in particular – two main systems have been identified; the integrated and the modular system (Ulrich and Eppinger, 2009; Sanchez, 2013). In the integrated system, every element is closely linked to the rest of the system. Modular architecture, in turn is defined by the statement, "Modules are units in a larger system that are structurally independent of one other, but work together. The system as a whole must therefore provide a framework – an architecture – that allows for both independence of structure and integration of function." (Baldwin, C. J. and K. Clark, 1999, p. 63). Thus, the modular system is divided into subsystems or modules which retain a relative independence from each other, while the components with each model interact closely with each other.

How can the complexity of these systems be formally represented?[10] The theory of complex systems provides a variety of possibilities (Holland, 1996; Kauffman, 1993; Mandelbrot, 1997; Watts, 1999). Following Kauffman (1993) and Frenken *et al*. (1998), any system is basically composed of a set of parts (***N***) and their relationships (***k***). Thus, the complexity of the system can be measured from both dimensions. The ***k*** dimension is, however, more important, since it reflects the possible combinations of **N**. [11]

Regardless of the number of components in an integrated system, the maximum number of relationships between them is ***k*.** That is, each component of the system is related to every other component. Formally ***k = N(N-1)/2***. In the case of a modular system, there are more relationships between the components within each model and fewer relationships between modules.

As a consequence, in an integrated system i) small changes to one design parameter can trigger multiple changes at the system level; ii) as a result, coordination and implementation costs of innovation are high; iii) the rate of change at the component level is therefore relatively slower than in the modular system; and iv) although the potential for innovation in the system as a whole is greater, and there is a probability of reaching a global maximum, to do so requires a number of additional conditions, in particular exceptional

[9] A study of the other two factors would require separate treatment. This is beyond the scope of the present analysis.

[10] The other method is related to the economic theory of specialized innovation in the analysis of integrated and modular systems (Baldwin and Clark, 1999; Sanchez and Mahoney, 2003). For analytical reasons and for greater conceptual and instrumental richness, the present study elects to use the theory of complex systems.

[11] To consider an example, a pulley system is actually a very simple system. Adding one pulley will exponentially reduce the force needed to move an object, but does not increase the complexity of the system. If a system had ten thousand pulleys, it could be argued that its complexity had increased but one could hardly say that it had increased significantly. On the other hand, a system such as a motor vehicle requires a great many components (about 10,000 parts) (Ulrich and Eppinger, 2009) that relate to each other in multiple ways and to different degrees.

organizational conditions[12] (Baldwin and Clark, 199; Sanchez and Mahoney, 2003; Ulrich and Eppinger, 2001; Lara and García, 2005).

In contrast, in the modular system i) changing one design parameter involves only one module, leaving the rest of the system unchanged; ii) which helps reduce development time and the cost of change; which increases flexibility and product diversification (differentiation); but iii) by reducing the probability of exploration, makes it possible that the final design chosen will be a local optimum but sub-optimal overall (Baldwin and Clark, 1999; Sanchez and Mahoney, 2003; Ulrich and Eppinger, 2001; Lara and García, 2005).

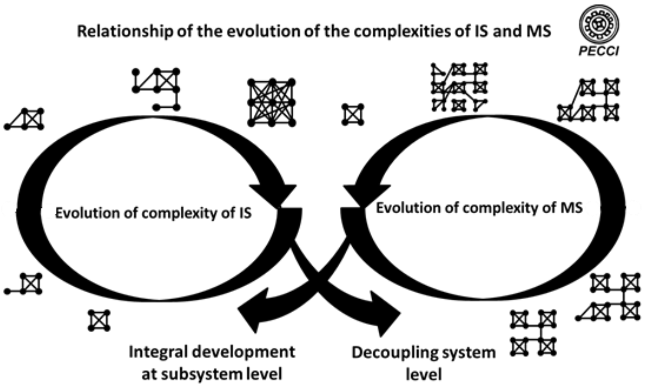
In studies of technological innovation, the academic debate has focused on whether the automobile industry could transition from an integrated system to a modular system (Fixon and Sako, 2001; Langlois, 2002; Pandremenos *et al*, 2009; Amatucci, 2015). This choice, however, is presented dichotomously; that is, the debate does not consider that a radical total change from one system to the other might be improbable and risky, nor that the disconnecting and reclustering of the components involved in modularization and the increase in complexity within sub-systems might be take place gradually. What if we do allow that such a challenging change could take place if it happened slowly and gradually? In the following sections, an explanatory scheme for the transition of an integrated system to a modular system is proposed under these conditions.

Complex links between integrated systems and modular systems

A system initially has a relatively low level of complexity (***N*** and ***k*** small), but as it has to deal with new problems, new components and relationships are added. For example, the first electric vehicles used traditional LSI lead-acid batteries (Lara and Salazar, 2013). Since these do not store enough energy, new types of batteries such as nickel–metal hydride, nickel–cadmium, lithium-ion and others (Reyes, 2012; Lara and Garcia, 2005) were tried. A new generation of advanced batteries was developed, requiring the design and integration of new safety and measurement subsystems. New designs expand the number of components and their relationships, increasing ***N*** and ***k***). But the most important aspect of this process is that the evolution of electric vehicles has led to one part of the system (batteries) decoupling from the rest and emerging as a new subsystem (Lara, 2014). New interactions develop inside this new specialized decoupled subsystem or module as they do within any integrated or modular system. These changes in the nature of the product also reconfigure the relationships between agents, making them more interwoven than before. This analytical approach is shown in Illustration 1.

Illustration 1.Evolution of complexity

[12] In the case of a technological system as complex as that of an electric vehicle, if the organizations and agents are to agree on a new product architecture, it requires all the stakeholders to concur and agree. But this is unworkable, since the system's capacities and carriers are distributed heterogeneously in different geographical spaces and technological fields.



Source: Prepared by autor. IS: Integral System, MS: Modular System.

So if this analytical perspective best represents reality, the integrated system versus modular system debate should be reframed. In the following section, invention in the development of electric vehicles is examined based on information contained in patents. Is it possible to empirically identify evolutionary processes in electric vehicles as summarized in Illustration 1? We believe it is.

Given the complex nature of what we seek to describe (summarized in Illustration 1), we have opted to apply network analysis to data extracted from patents registered in the United States patent office[13]. Network analysis can accurately describe the density in the area under study, the size of the entire structure of the system, and the emerging formation of different groups (subsystems or modules) on the basis of their relative proximity. This tool is useful to represent the evolution of the complexity of electric vehicles: the subject of the following sections.

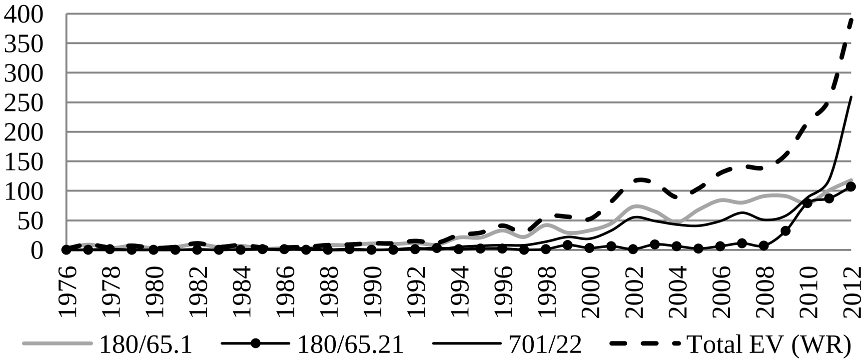
3. - THE INVENTION OF THE ELECTRIC VEHICLE

The history of electric vehicles began in the late nineteenth century, but the superiority of internal combustion vehicles discouraged further inventive growth in the direction of electric vehicles (Cowan and Hultén, 1996; Lara and Salazar, 2013; Calabrese, 2012; Chanaron and Teske, 2007; Chanaron, 1998). With fossil fuel prices rising since the 1970s and more and stricter standards for vehicle pollutant emissions imposed mainly in the 1980s and 1990s, the automotive industry needed to design new vehicle propulstion systems to replace the internal combustion engine (National Research Council, 2013; Lara and Salazar, 2013). Of all the alternatives that the automotive industry has considered, designing electric vehicles seems to

[13] United States Patent and Trademark Office (USPTO) patents were searched to provide the data for this study for two reasons; a) the U.S. patent data base is reliable and accessible; and b) the U.S. market being one of the largest in the world, it can be expected that all companies in the automobile industry will seek to protect their knowledge in that market. The database for this study was constructed by searching for all patents belonging to classes 180/65.1, 180/65.21 and 701/22. They were chosen because the USPTO itself classifies electric vehicles as belonging to these classes, according to its *Environmentally Sound Technologies Concordance* (ETS) (http://www.uspto.gov/web/patents/classification/international/est_concordance.htm accessed November 17, 2012). The database for this study has 2358 patents, dated from January 1, 1976 to November 20, 2012.
Each patent is classified according to the area of technical knowledge to which it belongs. Each patent office has both its own classification system and a classification system that follows the World Intellectual Property Organization (WIPO). Thus, when reference is made to class, it indicates which technological domain a patent belongs to. It should be noted that these patents include all EV; that is, not only those in the automobile industry but also medical devices such as wheelchairs, and electric ride-on toys for children. The latter types of vehicles are not removed from the analysis for two reasons: 1) the database would have been biased if a different, subjective criterion had been used; and 2) the ability to observe relationships between these vehicles and EV in the automotive industry would have been lost.

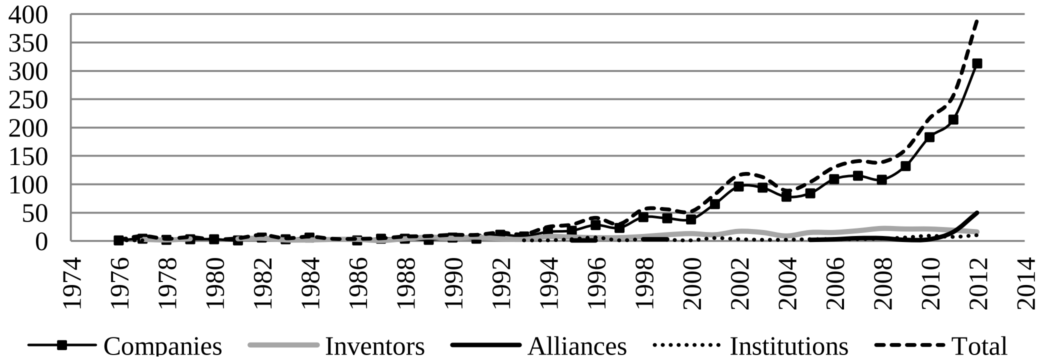
be one of the most vigorous, both for the inventions it has given rise to and for the incentives implemented by governments of the U.S., Japan and Europe (the regions where most of the main vehicle manufacturers are based) (Juliussen and Robinson, 2010; Lara and Salazar, 2013). In the early 1990s, invention activity, reflected in the number of patents, increased exponentially from 11 patents in 1990 to 389 in 2012 (see Figure 1) and from six different companies or business alliances that patented in 1990 to 97 in 2012 (see Figure 2).

Figure 1. Number of patents in EV (1976-2012)



Source: Prepared by author, data obtained from USPTO. UAM/PECCI database. “Sistemas Complejos Adaptables y Cooperación Tecnológica” Project, CONACyT No. I0017-156204. EV: electric vehicles. WR: Without repetition.

Figure 2. Number of patent agents in VE (1976-2012)



Source: ibid. The collective set of individual inventors makes up a single agent.

For some twenty years, most of invention activity was concentrated in class 180/65.1 (Motor vehicles; electric power). However, from 2008 to 2012, classes 701/22 (Data processing: vehicles, navigation, and relative location; electric vehicle) and 180/65.21 (Motor vehicles, electric power, Hybrid vehicle) have become the areas with the most activity (see Figure 1). This shows that the focus of invention activity in electric and hybrid vehicles is shifting from the design of tangible devices and mechanisms to data processing; this is because of the increase in electronically controlled units[14] (Juliussen and Robinson, 2010), a trend that is also affecting traditional vehicles (Lara, 2014).

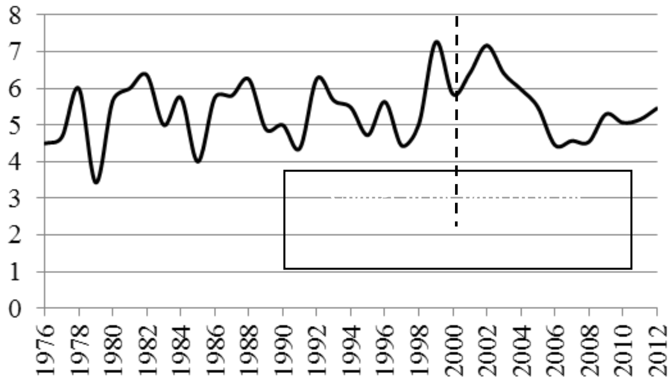
Technological classes can be interpreted as agents’ range or latitude of exploration and research[15]. In 1976, there were only eight classes of patents related to electric vehicles; by

[14] Known as ECUs

[15] The patents are classified according to the manual of each patent office. The classification refers to an area of knowledge; for example, USPTO class 701/22 refers to data processing in electric vehicles; class 180/65.1 refers

2012 there were 2394. Invention activity not only increased in volume, but also and especially expanded to explore new areas of knowledge and thus increased in complexity. The increase in the volume of classes can be considered to be associated with the increase in the number of patents. This statement is partly true, and explains only a part of the problem. If the classes are weighted by year, a pattern is seen in which, on average, there are periods when the classes increase and periods when they decrease (see Figure 3).

Figure 3.Class average for EV (1976-2012)



Source: ibid.

This pattern is likely due to the fact that when agents face particular problems, they explore new solutions, which is expressed in a higher average number of classes. This is consistent with the increase in complexity that takes place in an integral system when new components (**N**) and their potential relationships (***k***) increase. The new solutions, in turn, lead to new problems that require increasingly specialized solutions. This is reflected in a reduction in the average number of classes, which, in combination with the growing number of patents, involves a relatively greater increase in the number of relationships (***k***) than the number of classes (**N**). This produces a cyclical process of expansion/contraction of the average number of as a result of the growing exploration and specialization in technological knowledge, consistent with the process that synthesizes the relationship between integral and modular architectures described in the previous section.

4. - NETWORK ANALYSIS OF ELECTRIC VEHICLE PATENT CLASSES

To represent this phenomenon in more detail, an analysis using networks has carried out. This technique, part of the study of complex systems, enables the evolution of invention to be known with more precision. In the following, micropatterns in the evolution of EV classes are identified.

Simple micropatterns of the evolution of technology clases

USPTO patent examiners classify patents by area of knowledge. A patent can belong to one or more areas of knowledge[16]. This makes it possible to link one patent to another by the classes to which they belong[17]. Figure 4 shows the 1976 electric vehicle patents[18]; 3986095 and 3984742, with five and four classes respectively.

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to the area of knowledge associated with electric motors. There is no limit to the number of classes that one patent can have, and the more classes a patent has, the more specialized its knowledge can be considered.

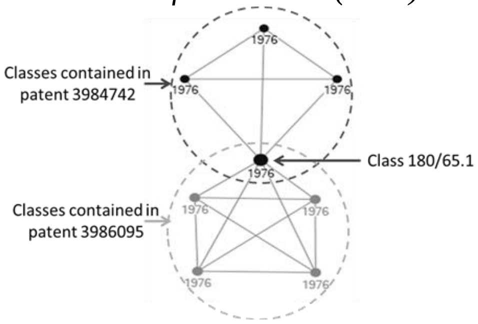
[16] There is no limit to the number of classes a patent can have. (See footnotes 5 and 6.)

[17] For example, suppose patent 1 is classified under A, B and C, and patent 2 under C, D and E. Then the two patents are connected by class C and the resulting network has 5 nodes (A, B, C, D and E) and 6 edges (AB, AC, BC, CD, CE and DE).

[18] The only two EV patents registered that year.

The first micro-pattern that can be observed is that configured by the ***clustering*** of classes[19]. The two patents have class 180/65.1 (Motor vehicles, electric power) in common, which is what links them. However, for one of the patents, this class represents 16.66% of all its links, while for the other it is only 10%[20]. Since the weight of class 180/65.1 is greater for patent 3984742 than for patent 3986095, it is grouped with the former.

Figure 4. Network of EV classes (1976): Clustering.



Source: ibid.

In a second example (Figure 5), for the period 1976–1978, three micro-patterns can be identified[21], which we term ***simple derivation***, ***relative autonomy***, and ***combination***. ***Simple derivation*** occurs when a set of classes that belong to the same cluster have a class in common that has a higher degree of connectivity[22]. ***Relative autonomy*** refers to the case when a set of classes belong to the same cluster but within it, connections are more dense in some classes than in others. ***Combination*** means that a set of classes that belong to one cluster shares classes with other clusters.

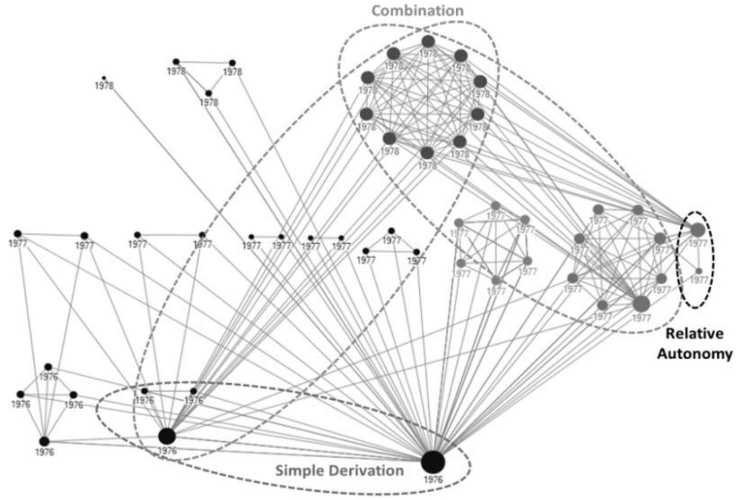
[19] This clustering results from applying the Clauset-Newman-Moore algorithm in NodeXL, which clusters nodes based on optimizing modularity (Clauset et al., 2004) in order to find the structure of the network.

[20] The total number of a patent's links (*k*) are calculated by *N(N-1)/2* where *N* is the number of classes under which the patent is classified. For example, in the case of the 1976 electric vehicle patents, patent 3,984,742 is categorized under 4 classes so the total number of links is 6. Each class therefore represents 1/6 = 16.66% of its total. Patent 3986095 has 5 classes, so it has 10 links and each of its classes represents 10% of its links. Since both patents are classified under class 180/65.1, the algorithm maximizes the relative weight of this node, meaning that this class (node) must be associated with the cluster in which it has greater weight. It is for this reason that i) the two patents are connected by class 180/65.1 and ii) this class having greater relative weight (16.6%) in the set of classes under which patent 3,984,742 is classified, it is clustered with these (dark points) and not with the set of classes under which patent 3986095 is classified (light points), in which it represents only 10%.

[21] These micro-patterns are recognized by applying the Clauset-Newman-Moore algorithm to identify the structure of the network.

[22] The degree of connectivity is the number of links that a node has. In our analysis of classes, for example, if a class has 12 links we say that its degree of connectivity is 12.

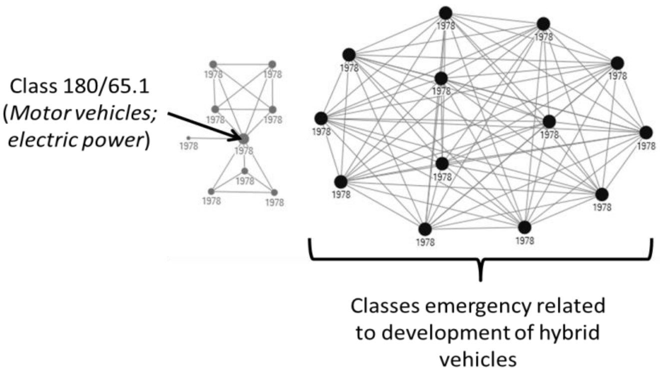
Figure 5.Network of EV classes (1976–1978): Derivation, relative autonomy and combination.



Source: ibid.

It is useful to represent phenomena emerging over a short period; for example during one year – 1978 (Figure 6). This was the year that a micro-pattern emerged of two clusters of ***unrelated classes***. This means that to design electric vehicles, agents explore new classes (knowledge areas) that are relatively unrelated, creating a more complex system. In particular, only four EV patents (4124086, 4123740, 4094377 and 4090577) were registered in 1978. They were categorized under a total of 22 classes. Three of them (patents 4124086, 4123740, and 4094377), classified under a total of 9 classes, are clustered around the class 180/65.1 (Motor vehicles, electric power) and the other group is patent 4090577 which is classified under 13 classes, all linked to the development of hybrid vehicles. This shows that 1978 is a point in time when disconnection was indicative of new technologies being explored[23].

Figure 6. Network of EV classes (1976): Unrelated classes.



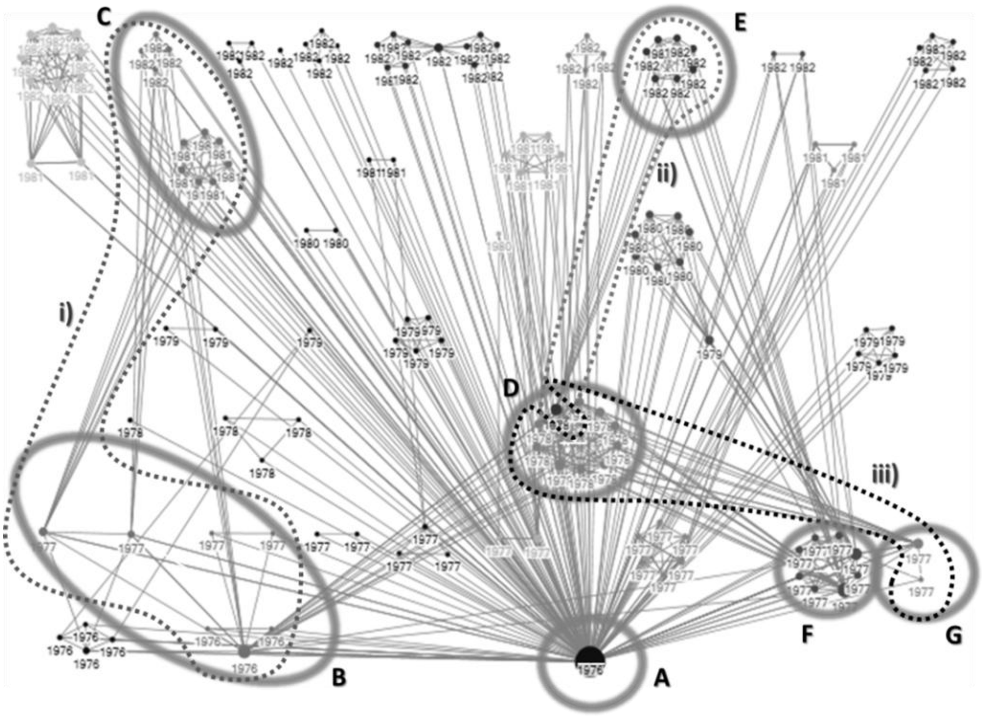
Source: ibid.

Another micropattern is that of ***reclustering***. This pattern happens when the emergence of new classes causes previous classes to change clusters. It may result from any of several different evolutionary paths. Some examples: i) classes that were derived from a previous class recluster with other classes[24]; ii) classes strongly connected with one cluster shift to

[23] This example illustrates that a low number of patents does not necessarily imply little inventive activity; the amount of activity is associated more with the volume of classes than with the number of patents.
[24] In Figure 7 it can be seen area A is derived from the classes of area B (cf. Figure 5), but when classes from area C emerge, those from B are reclustered with those of C because they have greater connectivity with the latter.

another[25]; iii) classes belonging to a cluster with relative autonomy move to another cluster while maintaining relative autonomy[26]. All these scenarios are seen in the electric vehicle network of classes for 1976–1982 (Figure 7).

Figure 7. Network of EV classes (1976–1982): Reclustering.



Source: ibid.

A complex macro-process of evolution of a technological system.

The evolution of micro-patterns affects the structure of the system as a whole. We are interested in determining whether this change corresponds to an integration and modularity process as described in Section 1. To do so, in this section we first visually illustrate the evolution of the system by time periods and then analyze it quantitatively.

1. *Visual representation of technological system evolution.*

For the visual representation of the evolution of the technological system of electric vehicles, the period under study has been divided into three stages. The first phase is from 1976 to 1995, the second is the interim period from 1984 to 2003 and the third phase from 1993 to 2012.[27]

[25] Figure 7 shows that one class which was previously strongly connected in D (cf. Figure 5), detaches and joins E because it is more strongly connected with the classes in that cluster.
[26] In Figure 7 it can be seen that the classes contained in area G which had relative autonomy from the classes of cluster F (cf. Figure 5) are reclustered with the classes of area D, maintaining their relative autonomy. This reclustering is due not only to increased connectivity between the classes in these two areas (D and G) but also because the relative weights of the classes in areas F and D due to the emergence of classes that are not linked to the classes in area G.
[27] These periods are chosen for the following reasons: i) each period is 20 years long, which is the validity period of patents; ii) we also see three stages in the evolution of the technological system; the initial, the intermediate, and the most recent stage; and iii) the periods overlap, which provides a certain amount of continuity, as part of the information from the previous period is carried forward.

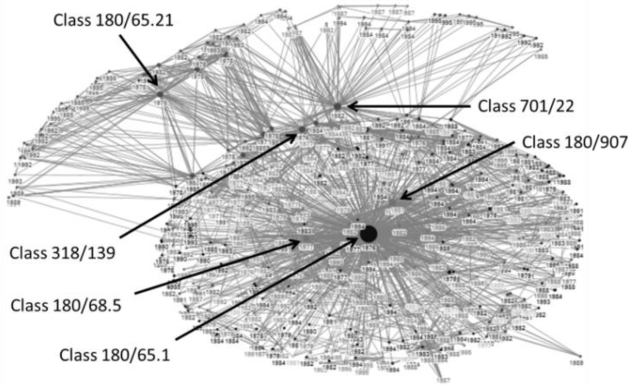
a) First stage (1976–1995)

In the first stage, the class 180/65.1 (Motor vehicles, electric power) dominates the connectivity of the whole system (see Figure 8.) while micro-patterns inside the system create subsystems or subclusters which are relatively more connected but show evidence of separation from the central subsystem. This is the case for three classes that belong to the same cluster but maintain relative autonomy as measured by their degree of specific connectivity: 701/22 (Data processing: vehicles, navigation, and relative location; electric vehicle), class 180/65.21 (Motor vehicles; electric power, hybrid vehicle) and class 318/139 (Electricity: motive power systems, battery-fed engine systems).

These three classes are in a cluster which gradually separates from the rest of the system and maintains a certain autonomy within the cluster, since this set of classes represents the key components of electric vehicles; namely, the electric batteries, the hybrid technology that links the internal combustion engine and electric motor; and the the data processor that manages power in the vehicle. In contrast, two other classes stand out for their high degree of connectivity; class 180/907 (Motor vehicles; motorized wheelchairs) and class 180/68.5 (Motor vehicles; power: battery mountings and holders). These are small rideable vehicles that show how incipient the development of electric vehicles was during the period, and indicate a certain disconnectivity in the system as a whole.

In summary, at this stage some uncoupling of subsystems can be observed to begin which contrasts with disconnectivity at the system level.

Figure 8. Network of EV classes (1976–1995): First stage (relative connectivity)



Source: ibid.

b) Second stage (1984–2003)

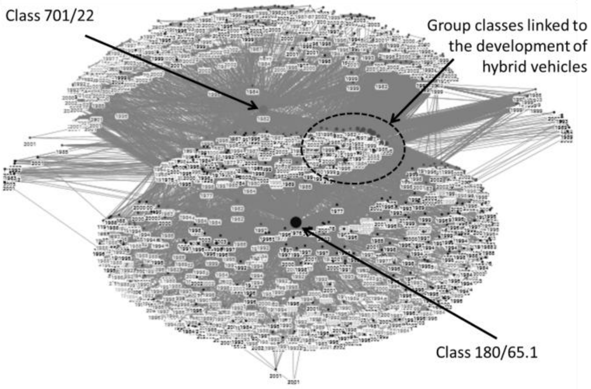
The second stage of the evolution of the system is made up of three different steps; the first showing a low level of invention activity (1984–1990), the second a take-off period (1991–1994) and and the third, in which invention activity displayed steady growth (1995–2000) (cf. Figure 1). The network at this stage shows three clearly separated subsystems, one associated with class 180/65.1 (Motor vehicles; electric power) which dominates the connectivity of the whole system; another led by classes 701/22 (Data processing: vehicles, navigation, and relative location; electric vehicle) and a set of classes related to hybrid vehicles[28] that show a more homogeneous degree of connectivity (see Figure 9).

[28] The first 20 classes in this cluster, in order of their degree of connectivity, are: 903/903, 180/65.27, 180/65.285, 180/65.28, 180/65.29, 903/906, 903/947, 903/916, 903/951, 903/910, 180/65.235, 180/65.25, 903/919, 180/65.245, 903/918, 903/946, 903/945, 180/65.6, 903/909 and 180/65.26. All classes that start with 903 belong to the class Hybrid electric vehicles, and the rest are nested in class 180/65.21 (Motor vehicles; electric power, hybrid vehicle).

The clusters are connected. Some classes are linked more with one cluster than either of the others, but there are also classes that are connected equally to two of the three main clusters, and some even with all three. During this phase, the cluster associated with class 180/65.1 has 1360 links with the cluster associated with class 701/22 and 1610 links with the cluster of classes associated with the development of electric vehicles. The two latter clusters, in turn, have 1088 links.

In summary, the micro-patterns generated a structure of clearly identifiably clusters or subsystems which are connected to each other in the system as a whole.

Figure 9. Network of EV classes (1976–2001): Second stage (connecting and ordering)



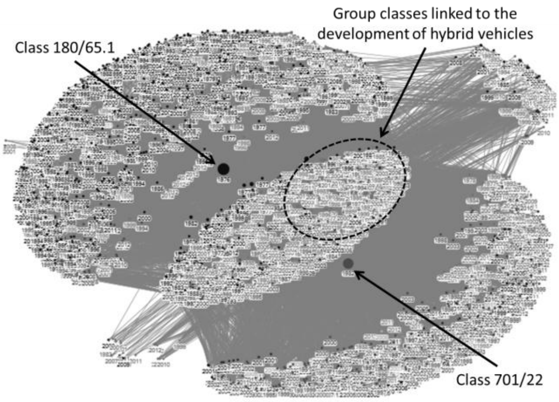
Source: ibid.

c) *Third stage (1993-–2012)*

The most recent stage includes periods of splitting off and accelerated growth in invention activity (cf. Figure 1). Visually, a similar structure to the previous stage can be observed (see Figure 10). However, two important elements can be noted. The first is that the cluster of patents associated with hybrid vehicles overtakes the cluster of classes related to class 701/22 (Data processing: vehicles, navigation, and relative location; electric vehicle). The two clusters exchange second and third place positions. Second, the growth of classes in the cluster of patents associated with the development of hybrid vehicles is distributed more clearly both in its cluster and the other two main clusters. There are 5160 links between the cluster of hybrid vehicle classes and the cluster associated with classes 180/65.1, and 5112 links between the former and the cluster associated with classes 701/22, while between the latter two there are only 1688 links. This means that in this stage, the micro-patterns have linked connected the network in such a way as to form three large, hierarchically connected clusters of classes.[29]

Figure 10. Network of EV classes (2002–2012): Third stage (hierarchical ordering)

[29] In contrast to Luo *et al.*, 2012), who show that there is no hierarchy in network transactions of the major automotive companies, we identify the network hierarchy of patent classes.



Source: ibid.

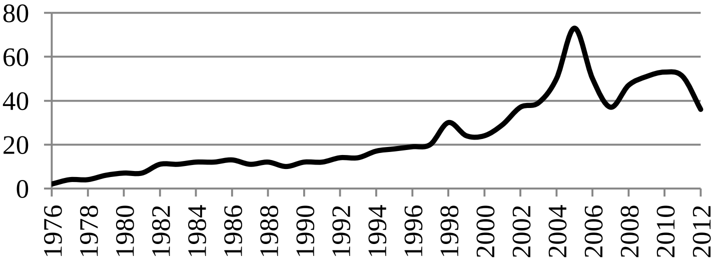
Once this set of micro-patterns has been identified, the evolution of the complete system of technology classes can be described as a result of the various instances of disengagement and integration occurring both locally and at the system level.[30] Assuming that the data on technology classes enables invention processes to be identified, this analytical perspective is relevant in several ways. First, it enables the complexity of invention activity to be represented not as a result of one agent or company's individual knowledge, but as the broad, diverse body of knowledge associated with a large number of patents and agents (see Figure 2). Second, the clustering and reclustering process of technological classes enables the evolutionary paths of technological knowledge to be examined. Finally, regardless of the scale (system or subsystem,) micro-patterns produce technological class integration/disconnection phenomena.

2. *Quantitative analysis of evolution of the technological system*

a) *Formation and development of clusters*

In the expansion process that technological classes undergo, the integration of clusters of classes is a fundamental piece of data for two reasons. First, because the number of clusters that form reflects the degree of connectivity of the subsystems; and second, because the position in which each cluster is located indicates investors' level of interest in developing the respective subsystem. It can be seen in Figure 11 how the number of clusters varies. In the second half of the 1970s, two clusters were formed but by 2005, the maximum number, 73, was reached. This means that during this period exploration of new classes accelerated, resulting in diversification of the clusters and the creation of new connections between subgroups. However, the reduction in the number of clusters in subsequent years suggests the consolidation of some subsystems.

Figure 11. Number of Groups in EV (1976-2012)



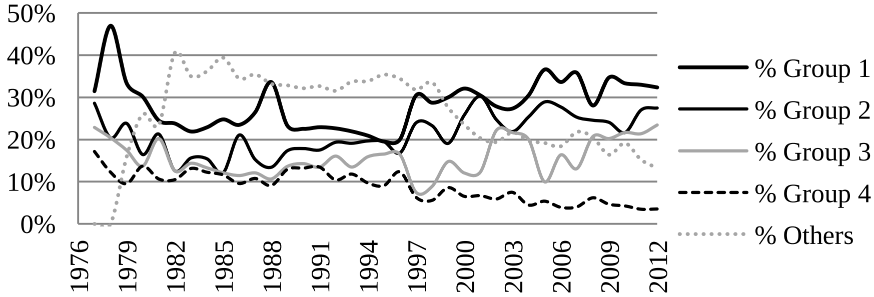
[30] Analogous to cell meiosis; the invention system is like a cell that reproduces with changes resulting from internal genetic recombinations (like varying combinations of classes), grows, and finally separates.

Source: ibid.

We might then ask how classes behave within clusters. To answer this question, these parameters must be observed: i) changes in the number of classes in each cluster; and ii) the permanence or stability of classes in their clusters.

i) Figure 12 shows how the number of classes varies within clusters[31]. From the figure we can highlight two phenomena. The first is that in the period 1976–1995, the number of classes per cluster tends to converge: the number of classes is similar in each of the four main clusters, ranging from 12% to 20% of classes per cluster. The second is that in the period 1996–2012 three clusters consolidated which together contained 83% of classes (32% of all classes in the first cluster, 27% in the second and 23% in the third). The formation of clusters with greater weight in the latter period may be associated with the creation of building blocks of the modular system, while in the former period it may well be associated with the explosion of new classes in the integrated system.

Figure 12. Evolution of the 4 main groups of EV (1976-2012)



Source: ibid.

ii) There is considerable circulation of classes in each subsystem. Nearly every class has changed clusters at some point. The histogram in Figure 13 shows the ranges of frequencies of classes changing clusters. A value near 1 means that classes have not changed cluster, and values near 0 means that they change cluster every year[32]. Note that only 0.002% of the classes have never changed cluster.[33] Thus although the network has changed as three major specialized areas consolidated (33.66% of classes have undergone relatively little change of cluster)[34], the low stability of classes within clusters is quite notable. That is, although the network is relatively stable at the system level, within clusters classes transfer from one cluster to another, a result of the introduction of new classes and their multiple relationships.

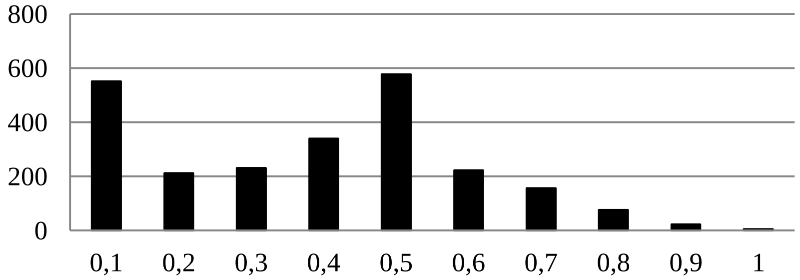
Figure 13Histogram of class variation between groups of EV.

[31] That is, the number of classes (as a percentage of all classes) contained in each of the four largest groups are counted.

[32] The histogram was calculated as follows. If a class changes cluster from one year to another, it is assigned 0, otherwise it is assigned 1. The data were averaged, and grouped into the corresponding decimal range. For example, the class 60/275 belonged to the clusters 22, 70, 47, 2, 29, 2, 3, 2 and 9 from 2004 to 2012. Since it changed cluster every year, it was assigned a 0 each year, its average is 0, and it is included in the range of values greater than or equal to 0 and less than 0.1. The class 310/156.58 was also present from 2004 to 2012, and belonged to the clusters 19, 20, 25, 19, 26, 21, 21, 21 and 4, so it was assigned values 0, 0, 0, 0, 0, 0, 1, 1 and 0. The average is 0.2222 and so it is included in the range of values greater than or equal to 0.2 and less than 0.3.

[33] In fact, only the relatively new classes (existing less than four years) had this characteristic.

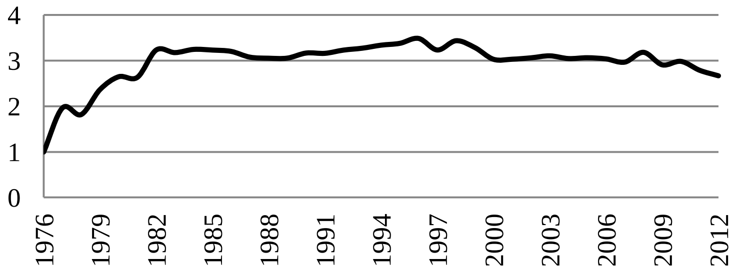
[34] Note that this change of cluster does not necessarily mean a class has moved from one cluster to another; it may be that the entire cluster has changed position relative to the system as a whole.



Source: ibid.

Based on this dual dynamic of the classes – stability of clusters in large areas (subsystems) and high mobility within – one might ask to what extent the system as a whole tends to show order or disorder. To answer this question, annual entropy[35] is calculated. In this case, it measures the degree of disorder of the system according to the interrelationships of the technological classes. From 1976 up to the early 1980s, increasing disorder can be seen in the system (see Figure 14). This behavior is explained by the the low volume of invention activity during this period; the inclusion of any one new class changed the whole system.

Figure 14. Entropia in the class system of VE (1976-2012)



Source: ibid.

During the rest of the 1980s and beyond, the entropy level was high but relatively stable up to an overall maximum of 3.48 in 1996[36]. However from 2000 on, entropy decreased steadily despite the large number of patents registered during this period. The reason for this is that the system became ordered into different subsystems, as described above. It grew from a small, temporarily less connected network into a more connected and ordered network (cf. Figure 14).

b) *Structure of the system*

The quantitative counterpart of the behavior of the system analyzed visually in this section is summarized in Table 1. This data enables us to examine the evolution and structure of the class network. The number of nodes is the number of classes (***N***). As this parameter grew exponentially in the period 1976–2012, so did the number of links (***k***). The data show that the diameters[37] of the network are significant. In the initial years (1976 and 1977) the network was highly connected (diameter 2), since there were few patents. From 1978 to 1992, the connectivity of the network decreased as its diameter increased from 3 to 4. Then from 1993 to 2012[38], network connectivity again followed an increasing trend (diameter 3, with higher

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[35] Entropy measures the degree of disorder of a system. Higher entropy means that the system is more disordered; lower entropy means it is more ordered. For this analysis, Shannon entropy (Page, 2011) was used.

[36] In 1992, the rate of invention became more intense and continued at a higher level. During this period the network evolved from a relatively disconnected network to a highly connected network.

[37] The diameter of a network is the maximum shortest path between any pair of nodes. It provides an insight into the connectivity of a network.

[38] Which coincides with the explosion in invention activity.

average geodesic distances). This increase took place despite the explosive growth of the network. If these results are compared with the network's density level and modularity[39], it can be seen that although the combined volume of classes is very high (2.86 million possible pairs) only 43 thousand pairs are explored. That is, the entire solution space is not explored, only a well-defined set of combinations associated with the nature of the technological problems that agents must deal with. For this reason, it can be claimed that the exploration space of electrical vehicle technological classes is ordered.

The same phenomenon is observed at the cluster level, except that diameter and density are greater within clusters. That is, there is more disconnectivity between groups although there is more exploration within groups, which is an indicator of internal disconnectivity[40]. Two aspects of this phenomenon can be noted; first, that complexity increases within subsystems; and second, that this forms an ordered structure of specialized subsystems.

We can thus can identify four permanent or stable subsystems beginning in 1995: 1) Electric motor design and development (class 180/65.1); 2) Data processing and power delivery (class 701/22); 3) Hybrid vehicles (mainly classes 180/65.21 and 903/903); and 4) Other electric vehicles (wheelchairs and small rideable vehicles related to class 180/907). These subsystems are interconnected in such a way as to form an ordered, hierarchical network of invention.

To this point, we can say that the patents encapsulate knowledge areas (classes) that provide technological solutions to specific problems. Micro-patterns that link the different areas of knowledge with different degrees of connectivity take shape from the accumulation of these solutions. In the process, invention activities emerge that move towards convergence (initially centered on the development of the electric motor), resulting in the emergence of clusters or subsystems. Thus, over time new solutions are created that open the door to new inventions that are ever more important. In this way, the knowledge network evolves in a dynamic, complex manner but ordered in particular areas (electric motors, processing data from various vehicle subsystems, and development of hybrid vehicles); moreover it is interconnected to form a hierarchy of subsystems. In the following section, the relationship between the complexity of technological classes and the existence of patent thickets and the anti-commons is explored.

Table 1. Statistical networks

[39] Which indicate potential places where connections can be added to the network.
[40] However there are significant differences between one cluster and another. The main cluster is more connected internally than the next, smaller cluster.

Year	Nodes	Unique Edges	Edges With Duplicates	Total of links	Nodes / Links	Self - Loops	Diameter	Average Geodesic Distance	Groups	Density	Modularity
1976	8	16	0	16	0.500	0	2	1.2500	2	0.5714	0.25000
1977	30	85	9	94	0.353	0	2	1.7356	4	0.2046	0.45326
1978	49	170	48	218	0.288	0	3	1.9692	4	0.1599	0.43027
1979	63	208	41	249	0.303	2	3	2.0257	6	0.1157	0.48352
1980	73	251	52	303	0.291	2	3	2.0349	7	0.1043	0.49483
1981	94	333	58	391	0.282	2	3	2.0448	7	0.0819	0.54281
1982	143	527	80	607	0.271	2	3	2.0923	11	0.0553	0.58821
1983	160	577	84	661	0.277	2	3	2.0855	11	0.0481	0.58298
1984	188	708	99	807	0.266	2	3	2.0961	12	0.0426	0.57944
1985	198	729	103	832	0.272	2	4	2.1704	12	0.0396	0.58707
1986	209	777	117	894	0.269	2	4	2.2172	13	0.0380	0.60587
1987	223	858	131	989	0.260	2	4	2.2870	11	0.0369	0.59414
1988	253	996	153	1149	0.254	2	4	2.2620	12	0.0332	0.58685
1989	271	1056	185	1241	0.257	2	4	2.2715	10	0.0309	0.58366
1990	280	1086	281	1367	0.258	2	4	2.2574	12	0.0304	0.54726
1991	297	1132	328	1460	0.262	2	4	2.2163	12	0.0283	0.53737
1992	336	1327	400	1727	0.253	2	4	2.2085	14	0.0259	0.51495
1993	356	1431	498	1929	0.249	2	3	2.2100	14	0.0252	0.48705
1994	402	1656	635	2291	0.243	2	3	2.1978	17	0.0231	0.47915
1995	441	1776	804	2580	0.248	2	3	2.2090	18	0.0209	0.46351
1996	535	2232	1023	3255	0.240	2	3	2.1933	19	0.0179	0.45520
1997	585	2479	1105	3584	0.236	3	3	2.2219	20	0.0165	0.47010
1998	662	2908	1442	4350	0.228	3	3	2.2151	30	0.0153	0.44444
1999	744	3617	2758	6375	0.206	3	3	2.2636	24	0.0157	0.41622
2000	811	4068	3296	7364	0.199	3	3	2.2705	24	0.0149	0.39908
2001	910	4943	4426	9369	0.184	4	3	2.2720	29	0.0146	0.34810
2002	1082	6709	6456	13165	0.161	5	3	2.2643	37	0.0140	0.34478
2003	1230	7789	8121	15910	0.158	6	3	2.2910	39	0.0126	0.33987
2004	1294	8325	9338	17663	0.155	7	3	2.2863	50	0.0122	0.31837
2005	1392	9021	10409	19430	0.154	9	3	2.2793	73	0.0115	0.32729
2006	1473	9623	11210	20833	0.153	10	3	2.2729	50	0.0109	0.32602
2007	1587	10396	11979	22375	0.153	11	3	2.2875	37	0.0101	0.33514
2008	1662	11069	12982	24051	0.150	15	3	2.2783	47	0.0099	0.31821
2009	1800	12348	14658	27006	0.146	17	3	2.2705	51	0.0095	0.32961
2010	1922	13682	16634	30316	0.140	24	3	2.2809	53	0.0093	0.31698
2011	2124	15957	19115	35072	0.133	33	3	2.2816	51	0.0088	0.31154
2012	2394	19669	23895	43564	0.122	57	3	2.2773	36	0.0086	0.30329

Source: ibid.

5. - COMPLEXITY, PATENT THICKET AND ANTI-COMMONS IN EV

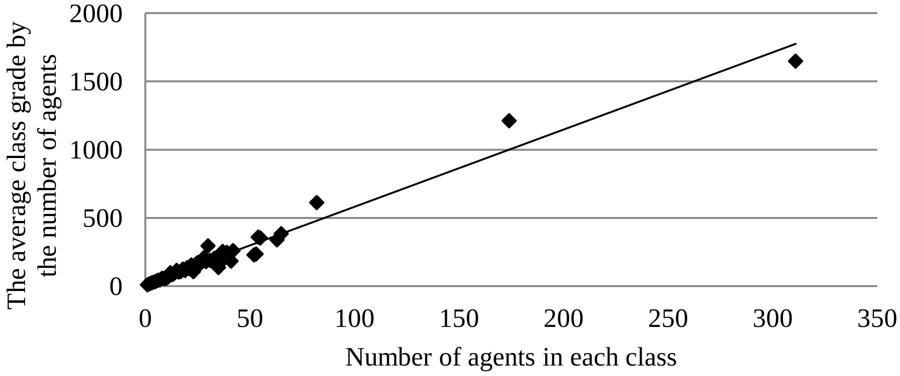
The results presented in the previous sections illustrate the complex nature and evolution of electric vehicles. However, it must be asked whether a relationship exists between this complexity and the possible existence of the patent thicket. In particular, is there a relationship between the connectivity of classes (knowledge areas) and the number of agents participating in each class? If so, the degree of connectivity of the classes acquires a new importance. If the degree of connectivity of a class (the number of classes it is connected to) is low or if the degree of connectivity is very high but there are few agents, then there will likely not be a patent thicket. But if the degree of connectivity is high and there are many agents, then we claim that a patent thicket is more likely.

Let us consider the evidence. In total, 411 different agents have participated in electrical vehicle invention activity[41]. This means that each agent is associated with an average of 5.82 classes. However, the distribution is not normal; it is a power-law distribution: there are a very few classes that contain many agents (or alternatively, many

[41] Agents can be companies, research centers (public or private), universities (public or private), government organizations, or independent inventors (considered as a single agent in our analysis).

agents are concentrated in a few classes) and many classes with few agents. For example, class 180/65.1 has 311 agents (75.66% of all agents) while there are 1499 classes (62.61% of the classes) that have only one agent each. The mean of this distribution is 2.98 which is, in terms of the patent thicket, a relatively low number. Therefore, if we only consider the mean, each agent would have to negotiate with a maximum of three additional agents to cover all the patents in a class.

Figure 15. Grade average vs number of agents



Source: ibid.

However, the evidence shows that there is a strong relationship (R2=0.967) between the degree of connectivity of a class and the number of agents participating in that class (cf. Figure 15). We will describe why this is. Electric vehicle developers face numerous problems, some of them relatively simple and others highly complex[42]. When the problem is complex, 1) no agent can fully solve it (at least in the short term); 2) the problem is divided into simpler sub-problems which can be addressed; and 3) the solutions to the sub-problems are complementary. Thus, at the sub-problem level, there are two possible cases; a) multiple solutions emerge from exploring various technological fields; or b) multiple solutions emerge from a common set of classes. These two possibilities imply that a sub-problem can be solved by many different groups of classes and that a single cluster of classes can solve different sub-problems. Thus the classes are connected according to the degree of complementarity of the sub-problems. Agents select the problems and technology areas (classes) that they can solve according to their abilities and interests. In particular, automotive assembly companies have patented in only a small proportion (11.48%) of classes, but the average degree of connectivity of these classes is 66.6. This is approximately three times the average connectivity of 20.5[43]. In all these processes the probability is greater that the complex nature of the problem will lead to the formation of a dense network of overlapping classes and property rights (patent thicket).

CONCLUSIONS

To investigate the existence of the patent thicket in electrical vehicle design and development during the period 1974–2012, this study proposes a way to represent the evolution of technological knowledge based on integrating Ostrom's theory and the theory of complex systems. From information gleaned from the patents – in particular their classification by technology classes – the technological evolution of electric vehicles was reconstructed. It was

[42] For example, the development of the electric motor and of the energy storage system (batteries).
[43] Data source: UAM/PECCI database. "Sistemas Complejos Adaptables y Cooperación Tecnológica" Project, CONACyT No. I0017-156204.

found that technological knowledge was incorporated/split into increasingly complex subsystems. The main findings are summarized in the following paragraphs.

The evidence enables at least six stages to be identified in the evolution of electric vehicle technological knowledge during the period under study. In 1976–1982, invention activity was low (41 patents), with a disconnected knowledge/classes network. In this state, the incorporation of even a single new class increased the entropy of the network. From 1983 to 1990, the knowledge network remained virtually unchanged (54 patents registered). These first two stages can be characterized as a phase of low invention activity, with a small and relatively disconnected network.

From 1991 to 1995, invention activity increased (92 patents), but only in some areas (233 classes). The increases occurred particularly in two areas relatively disconnected from each other – electric motors and small vehicles. From 1996 to 2000, invention activity and the areas explored for solutions expanded (235 patents and 510 classes). Essentially, the weight of the class related to data processing increased. During these two periods the network of classes increased in size and connectivity.

From 2001 to 2005, a significant phenomenon occurred: the number of patents (504), classes (879) and subsystems (from 29 in 2001 to 73 in 2005) all increased, but the level of entropy did not (during the period its minimum was 3.02 and its maximum 3.1). This was a period when more defined subsystems began to emerge but did not fully integrate. The network began to be ordered. Three phenomena that occurred from 2005 to 2012 can be noted. The first is that the number of subsystems dropped (73 to 36), as did the level of entropy (3.06 to 2.66). The second is that the data processing subsystem maintained its upward trend and relative autonomy with respect to the system (with a degree of connectivity of 943 for the class 701/22, the second most connected class) but moved down to fourth place in relative size among clusters. The third is that the set of patents related to development of hybrid vehicles had the connections of all the major subsystems (9407 connections to the four major clusters). Taken together, these three factors mean that the network became more hierarchical.

In summary, the knowledge network associated with the development of electric vehicles went from being small and relatively disconnected (1978–1990), to being more connected (1991– 2000), to being hierarchically connected (2001–2012).

One of the virtues of network theory is that it enables the complexity of the evolution of technological knowledge to be reconstructed. It is useful for explaining how the process of incorporating new technology classes into the network of classes occurs through micro-patterns. It is through the existence of different micro-patterns that the emergence of subgroups or technological sub-systems can be explained.

The more internal interactions a subsystem has with the rest of the subsystems, the more it is likely to be consolidated, differentiated from the others, and even to dominate the overall system. This narrative summarizes the relationship between the integrated and modular design models in a complex technological system. In this study, the emergence of three important subsystems in electrical vehicle development is identified and described. These subsystems are associated with the development of the electric motor (currently the dominant subsystem), with data processing (which may come to dominate the industry) and with the development of hybrid vehicles (which has become more important in recent years).

It is precisely in these subsystems where both high connectivity between classes and higher density (population) of agents can be observed, which is a clear indicator of the presence of the patent thicket. In fact, it has been shown that for the case of electric vehicle invention activity, there is a direct relationship between the degree of connectivity of classes and the number of agents participating in them. A total of 411 agents participate in the network; companies, alliances, universities, research centers, governments and individual inventors. This diversity of agents means that there are a variety of different types of relationships between them; however, the data show that rival automobile companies have patented in 11.48% of the classes that are characterized by a high degree of connectivity (66.62). Thus it can be said that there is complementary knowledge (high connectivity) and fragmented knowledge (owned by different rival automakers) in the development of electrical vehicle invention activity, which points to the existence of an anti-commons scenario. The solution to the anti-commons requires innovative institutional arrangements that avoid deadlock between companies.

In summary, the theory of complex systems enables identification of the existence and evolution of a dense network of technological knowledge, intellectual property, and agents in the development of electric vehicles. Network theory, in particular quantitative measures of the evolution of the network, have enabled us to describe the relationship between the nature of the good and the patent thicket problem and the problem of the anti-commons with greater rigor.

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