Technological discontinuities and incumbents' sourcing strategy: the case of electric batteries in the automotive industry

Abstract

Objectives. *Electric vehicles (EVs) affect car technologies and architecture and, in turn, carmakers' core competences especially as regard power train technologies. Carmakers have traditionally distinctive competences in the design of internal combustion engine vehicles (ICEVs) but not in the batteries technology. This paper explores how the three biggest carmakers (Toyota, Volkswagen and General Motors) managed their sourcing strategy to cope with this technological discontinuity.*

Methodology. *We use a longitudinal research design and secondary sources to disentangle two separate domains: the technological evolution of batteries and the evolution of three carmakers' sourcing strategy. Both dimensions are then represented and compared using the "life-cycle" model.*

Findings. *This paper contributes to the innovation and supply chain management literature by describing how carmakers' sourcing strategy evolved during a period of technological discontinuity and in a context characterized by a high technological uncertain. Results suggest that carmakers followed a three-steps sourcing strategy characterized by an inversed u-shaped breath of suppliers base and that this u-shaped breath is correlated to the batteries' technology life-cycle.*

Research limits. *The study includes top carmakers but not all incumbents that operate in the EVs segment. Also the study relies on secondary sources.*

Practical implications. *Managers can rely on the "life-cycle" model of sourcing strategies to plan and analyze their portfolio of partners depending of the level of technological uncertainty.*

Originality of the study. *To the best of our knowledge, this study is the first to use the "life-cycle" model to compare incumbent firms' sourcing strategies at different levels of technological fluidity.*

Key words: *batteries; electric vehicles; sourcing strategy; technological discontinuities; product life-cycle.*

1. Introduction

How did carmakers manage the sourcing of electric batteries during a period of high technology uncertainty? This is a relevant research question because carmakers have core competences in the design and production of Internal Combustion Engine Vehicles (ICEV), while they historically lack the knowledge of cells and battery packs that are the distinctive components of Electric Vehicles (EVs). In this context the positioning of incumbents (the carmakers) may be threatened because new technologies make existing competences (at least partially) obsolete (Tushman and Anderson, 1986).

Electric and hybrid vehicles constitute an example of discontinuous technology. Electric vehicles require both architectural and component changes, while hybrid vehicles are often built on pre-existing platforms and include a new power train technology. But both types of EVs require a shift from combustion engine to electric propulsions. This shift interrupts the display of the automotive industry characterized by long-term incremental improvement of core technologies. The incremental trajectory of the industry prevailed since the introduction of Model T. Carmakers added equipment for emissions treatment and efficiency enhancement, but maintained conventional motorizations. In the core activities of the automotive makers, the internal combustion engine has remained largely unchallenged ever since almost 100 years ago (Fujimoto, 2014). Nevertheless this pattern changed in the last 10 years due to new stringent legislations, a renewed increase of fuel prices and the higher attention of clients and media toward environmental issues. These forces pushed incumbents and new entrants, such as Tesla, to initiate a technology-based competition focused on the technological innovation in the very core component of the vehicle, the automotive power train. The introduction of new and competing technologies, such as nickel and lithium batteries, in this mature industry generated an era of ferment and fluidity (Anderson and Tushman, 1990), characterized by increased technological experimentation and uncertainty (Bergek *et al.,* 2013). Batteries technology is still evolving and their performance, weight and cost are crucial for electrified vehicles. In the last years, carmakers have been investing in two main technologies: the nickel-metal hydride (Ni-Mh) and the lithium (Li-Ion) batteries. The Ni-Mh is a technology developed during the 80s and today is a mature technology. The Li-Ion technology is still under development and seems having great potential. Today the Li-Ion technology is the most diffused technology for laptops and mobile phones and has become widespread also in the automotive industry (Herrmann and Rothfuss, 2015; Schott *et al.,* 2015). While the electric and hybrid vehicles market is expected to increase further, there is still uncertainty about future volumes and also some skepticism about the impact of these technologies on the environment: the cost of electricity as well as the emissions produced to generate it do vary from countries to countries and the recycling of batteries is expensive and complex (Steinhilber *et al.,* 2013).

Overall, the market of EVs is highly uncertain from the demand, supply and technology side. In this paper we aim at increasing our understanding about how incumbent firms managed their sourcing strategy during this cycle of technological discontinuity (Anderson and Tushman, 1990). In this respect we mainly focus on incumbents' open innovation search strategy analyzing the breath of their search strategy (Laursen and Salter, 2006) and how they managed and control external relationships (Dyer and Singh, 1998; Paulraj and Chen, 2007; Parmigiani, 2007). This paper explores how the three biggest carmakers, Toyota, Volkswagen (VW) and General Motors (GM), managed their sourcing strategy in this setting. Interestingly enough, despite the differences in the analyzed carmakers' EVs strategy, we identified a similar pattern in their sourcing strategy. The analyzed carmakers first selected few external partners, then they explored the technological landscape by engaging multiple partners in strategic alliances and finally they selected few technologies and suppliers eventually starting a concurrent sourcing strategy. Results suggest that carmakers followed a sourcing strategy characterized by an inversed u-shaped breath of suppliers base and that this u-shaped breath is correlated to the batteries' technology life-cycle. Finally, all carmakers gradually increased their control over batteries technology by moving from market to hierarchy.

Overall, this paper contributes to the innovation and supply chain management literature by identifying a sourcing strategy that correlates with Abernaty and Utterback (1990) product life-cycle thus increasing our understanding about incumbents sourcing behavior in highly uncertain environments. In an era of a rapid technological evolution of multiple complex products and services, such as robots or virtual reality, it becomes crucial to understand how established firms manage their sourcing strategy and how this strategy evolves with the technological landscape. Also this paper contributes to supply chain management and open innovation literature by describing how incumbents rely on external sources of innovation and how they approach evolve in time with the technology. Open innovation literature emphasize the relevance of external sources of innovations but some authors also argued that too many partners may be detrimental. Accordingly, in this paper we suggest that the breath of external search strategy has an inverted u-shape relationship with time and that many partners are beneficial only during specific phases of technology evolution (Laursen and Salter, 2006; Katila and Ahuja, 2002). Finally the paper contributes to the supply chain management and modularity literature by supporting the mirroring hypothesis in the case of integral products and by emphasizing the relevance of the most recent contributes that ask for a contingent view of the mirroring in which technological uncertainty is central in shaping sourcing strategies (Furlan *et al.,* 2014).

The paper is organized as follows. The next section debates sourcing strategies in technological uncertain environments. Then the research design is presented. In the findings section we present the supply strategies of the three selected carmakers (Toyota, General Motors and Volkswagen) while the discussion and conclusion section compares the three strategies and identifies the main theoretical and managerial implications.

2. Technological discontinuity and sourcing strategies of incumbent firms

Today batteries technology is still evolving and uncertainty is high (Magnusson and Berggren, 2011). Competing technologies are compared along several dimensions, such as safety, performance and cost, and among these variables several trade-offs exist (Hermann and Rothfuss, 2015). Carmakers have not specific competences in batteries design and production. The effect of discontinuous technological change on existing industries is a central topic in the literature on technological development and industrial innovation. Technological discontinuities can lead to intensified competition because ex-ante established technologies of incumbents are, at least partially, substituted by new knowledge endowments and competences (Abernathy and Clark, 1985; Anderson and Tushman, 1990). As a consequence, a period of uncertainty and fluidity about new technologies and market leaders starts. One of the most cited frameworks depicting the dynamic pattern of industrial innovation is the Abernathy-Utterback model of the "industry life cycle" (Abernathy and Utterback, 1978). In this model the authors hypothesize that industries face cycles of technological discontinuities characterized by a wave of numerous technologies followed by the selection of a dominant design. In the automotive industry the dominant design is constituted by the 1908 Ford Model T (Fujimoto, 2014). When a "dominant design" is selected and the technological uncertainty is reduced, the focus of competition shifts from product to process innovations. At this "specific stage" of the industry life cycle, the focus of competition becomes economies of scale and unit production costs.

In this paper we are interested in the first wave of innovation, which focuses on products. The product life-cycle model is graphically illustrated as a hilly curve representing the frequency of product innovations that flats when a dominant design emerges. Incumbents are mainly trigged by the pick of this wave especially when new technologies require competences distant from incumbents' endowment. The literature argues that incumbents fail when innovations are "competence-destroying" and render their existing knowledge base (at least partially) obsolete (Tushman and Anderson, 1986). Industry incumbents are burdened with "core rigidities" and the legacy of old technology (Leonard-Barton, 1992). Therefore, technological discontinuities may open up possibilities for new entrants. Hence key questions follow: How do incumbents, lacking new core competences, manage their sourcing strategy during the wave of technological fluidity? Which is the carmakers sourcing strategy for electric batteries? How did this strategy evolved in time?

Various authors in the competence perspective suggest that incumbents use alliances to expand their set of distinctive capabilities and engage suppliers in an intense knowledge and information sharing (Lee, Liang and Liu, 2010). Hence inter-organizational learning is a mechanism through which incumbents acquire the competences necessary to survive in the new technological paradigm (Hamel, 1991; Hodgson, 1998; Kogut, 1988, Russo, 2012). Alliances may be instrumental in a) transferring existing knowledge from external suppliers of new technologies to incumbent firms, thus allowing incumbents to build absorptive capacity and internalize new competences (Khanna *et al.,* 1998); b) creating synergies and mixing multiple external sources of innovation by building on an open innovation framework firms with multiple partnerships have more chances to develop new technologies (Laursen and Salter, 2006). Technological innovation implies problem-solving activities that involve the creation and recombination of multiple ideas and knowledge bodies. External partners can bring to incumbents complementary capabilities, which generate unique synergies. Firms sign alliances to create knowledge and integrate knowledge (Dyer and Nobeoka, 2000; Dyer and Singh, 1998; Grant and Baden-Fuller, 2004; Das and Teng, 2000).

Carmakers typically buy their components from few selected first tier suppliers with whom they have collaborative relationships (Zirpoli and Becker, 2011; Goffin *et al.,* 1997). But in case of electrified vehicles carmakers face, for the first time after decades, a high level of market and technological uncertainty. In this context, we still lack studies that look at how carmakers managed and structured their exchange relationships with battery suppliers or directly with components producers (Ulrich and Barney, 1984). Specifically we do not know which was the breath of carmakers' external search (i.e. how many partners they involved (Laursen and Salter, 2006)) and the contract form they selected to collaborate with suppliers. The external search breadth is the number of external sources or search channels that firms rely upon in their innovative activities. Laursen and Salter (2006) suggest that external search breadth is curvilinearly (taking an inverted U-shape) related to innovative performance. While multiple partners improve firms' knowledge endowment too many partners may generate an over-searching that may have a negative influence on performance. Firms with a too broad search strategy may have too many ideas to manage that cannot be fully exploited. Hence there is a point at which external search breadth becomes disadvantageous.

Furthermore carmakers need to define how to manage such external relationships. Carmakers may move from market-based transactions to supply relationship strategies that ensure a higher level of control over resources to minimize dependence on other firms (Dyer and Singh, 1998; Paulraj and Chen, 2007; Walter and Veloso, 2008). As suggested by Dyer and Sight (1998) effective governance can generate relational rents. A governance is effective when partners are able to align their governance structure with the nature of their transactions. Under a resource dependence theory point of view transactions are evaluated on the basis of control that the buyer needs to exert over the supplier. If a firm is deficient in a particular resource that is essential for gaining a competitive advantage, then the firm will take purposive actions to acquire the resource, such as engage suppliers in joint ventures, alliances, M&As or long term contracts through which stabilize their relationships, share knowledge and information and align incentives and risks (Eisenhardt and Schoonhoven, 1996; Paulraj and Chen, 2007; Reid *et al.,* 2001). Moreover, supply chain management is crucial to foster the firm's resources and competences combination with the complementary resources of their suppliers. This unique combination of complementary assets may be a source of competitive advantage (Harrison *et al.,* 1991; Huang *et al.,* 2014; Paulraj and Chen, 2007). Particularly, technological uncertainty and dynamism may require hand-in-glove relationships with suppliers to integrate their innovative components into the car's architecture (Cabigiosu, 2013; Furlan *et al.,* 2014; Cabigiosu *et al.,* 2013). These are typically supply relationships in which buyers and suppliers share high-powered integration tools, such as crossorganizational or co-located teams (Dyer, 1996; Helper 1991; Narus and Anderson 1995). Batteries need to be inserted into the car's architecture and technology and this requires the pooling of buyer and supplier's knowledge bases and expertise. Carmakers do not only face the problem of selecting the most promising batteries' technology: carmakers need to learn how batteries perform and interact with the other car's components that are model-specific. And knowledge sharing and learning ask for tightly coupled relationships or a concurrent sourcing strategy (Cabigiosu, 2013; Furlan *et al.,* 2014; Parmigiani, 2007). Bensaou and Anderson (1999) suggest that firms prefer specific investments under a greater pace of technological change because firms refusing to bet until late in the horse race may find themself too late to place any bet at all. Buyers may find no available supplier. Also, strategic partnerships can help firms to leverage their reputation and legitimacy, as in the case of EVs (Eisenhardt and Schoonhoven, 1996). Overall, the literature suggests that uncertainty increases buyers' convenience to engage suppliers in strategic alliances. Carmakers may establish strong links with suppliers and have exclusive access to their know-how, technology, and production. However, relationships of this kind can limit a carmaker's ability to react quickly to technological advances achieved by other players. Hence, the supplier's selection process becomes a central issue.

This paper, by analyzing the three biggest carmakers, sheds light on how incumbent firms manage their sourcing strategy during a cycle of technological discontinuity (Anderson and Tushman, 1990). In this respect we mainly focus on incumbents open innovation search strategy analyzing the breath of their search (Laursen and Salter, 2006) and the contractual forms used to manage and control external relationships (Dyer and Singh, 1998; Paulraj and Chen, 2007; Parmigiani, 2007).

3. Research design

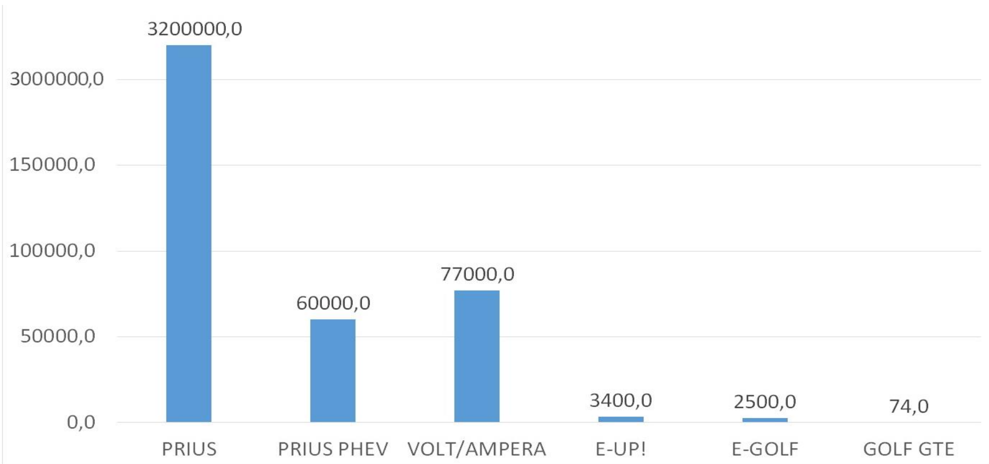
Studying how sourcing strategies evolved in time in a context of technological fluidity demands a detailed understanding of the change processes themselves that occur within the technical domain and the industry domain. This, in turn, requires a longitudinal research design (Poole *et al.*, 2000). Our research framework fundamentally establishes two separate domains: the technology evolution and the evolution of incumbents sourcing strategy. In the technology domain already exists studies that analyze the development of batteries technology using the "life-cycle" framework (Schott *et al.,* 2015, Sierzchula *et al.,* 2012), while we still lack studies that look at sourcing strategies. As far as batteries technology is concerned, we know that lithium-ion technology became the leading technology by 2011 and literature already provides a life-cycle model of this technology (see Figure 6). Hence we are interested in understanding how carmakers managed their sourcing strategies before (during the highest technological uncertainty) and after 2011 (when uncertainty was reduced) and to create a life-cycle model of sourcing strategies to be compared with the life-cycle model already available for batteries.

To build the life-cycle model of sourcing strategies we used secondary sources to grasp incumbents' strategy along two dimensions: a) the breath of sourcing strategies, which is measured as the number of partnerships in each year. We considered all types of partners, from suppliers to competitors, for the development and/or production of batteries (Laursen and Salter, 2006) and b) the contractual form dimension (how carmakers managed their supply relationships, e.g. via alliances, mergers, long-term contracts, etc.). We then created a "life-cycle" model for sourcing strategies in which the x-axis represents the time and the y-axis represents the number of incumbents' external partners for the supply of batteries (the breath). We created this graph for each car-maker and then we synthesized our findings in one unique graph. While the graphs focus on the breath of sourcing strategies, we used the information about contracts, and how carmakers managed their relationships with each partner, to have a more in-depth understanding of the nature of each supply relationship or collaboration identified and hence of the carmakers' sourcing strategy. We finally compared the technological and sourcing strategy "life-cycle" models (Abernaty and

Tushman, 1990) to understand if and how technological and sourcing trajectories are correlated before and after 2011, the threshold of technological uncertainty.

Particularly, this article analyses the supply chain strategies for batteries of three carmakers: General Motors, Toyota and Volkswagen. These carmakers have been selected because they represent the top selling carmakers, different strategies as regard electrified vehicles and the three most relevant geographical areas as long as the carmakers history is concerned (US, Japan and Europe). The United States is the largest electric car market in the world. The results of the sales in the US in 2014 show that among the most sold electrified cars hybrid vehicles there are the Toyota Prius Liftback and the GM Chevy Volt (http://fortune.com/2015/01/08/electric-vehicle-sales-2014/). VW does not appear in the 2014 ranking because they only recently entered the market with the electric models E-Up! and E-Golf. In 2014 in Europe the two models obtained the 5% and the 3%, respectively, of the electric vehicles market share (http://evobsession.com/europe-ev-sales-update-october-sales/). Figure 1 synthesizes the cumulative sales of the most sold electric and hybrid models of the three analyzed carmakers from their launch to the end of 2013. Toyota is the carmaker that most heavily invested in electrified cars, followed by GM, which worldwide has a strategy similar to that of many other carmakers that entered soon the market but without heavy investments, and finally we find VW that entered later.

Fig. 1: Cumulative sales of the main electric and hybrid vehicles of the analyzed carmakers



Source: Our elaboration.

We collected the data about the three OEMs supply strategies by analyzing multiple dataset till the end of 2014. The aim of the research was to analyze how carmakers managed their supply strategies for batteries/cells since when they started investing in EVs, when the uncertainty of batteries technology was significantly reduced in 2011 (Sierzchula et al. 2012) and how their strategy changed in the subsequent years till the end of 2014. First, we run a broader research on Business Source Complete (BSC), "Il Sole 24 Ore" and "The Economist" by entering different combinations of the following keywords: hybrid, "electric vehicle", carmaker, OEM, partnership, "supply relationships", batteries, "cell manufacturer". This research helped us in gathering data and making sense of recent trends in the EVs industry and in identifying the main sources information and news about carmakers sourcing strategies. We then focused our analysis on the partnerships that GM, Toyota and VW signed for the supply of batteries and we performed this second research mainly on Business Source Complete, Automotive News (www.autonews.com), Green car congress (www.greencarcongress.com), Green car reports (www.greencarreports.com), Hybrid cars (www.hybridcars.com), Edmunds Auto Observer (www.edmunds.com/autoobserver-archive), EV Obsession (www.evobsession.com) using as keywords: General Motors (or Toyota or Volkswagen) and electric battery (or cell) and cooperation (or contract or partnership or supplier or joint-venture or M&A). Furthermore we performed targeted researches in the web sites of the three carmakers.

This procedure allowed identifying the main collaborations that the three carmakers activated for the supply of batteries, their technological choices and the formal partnership/contract used to manage such relationships. Once the suppliers have been identified we surfed the web and their websites to collect further information about them. Overall, we collected about 300 documents including reports and articles. The data collected about supply relationships where organized using temporal lines in which to report, for each OEM, the year in which a supply relationship for the provision of batteries has been activated and, eventually, when it ended. Each supply relationship has a distinctive color. These temporal lines allow quantifying the number of supply relationships and partnerships for batteries activated by each OEM and hence evaluating each OEM research breath (i.e. the number of partnership each year).

A histogram, the "life-cycle" model of sourcing strategies, synthesizes the overall number of supply relationships observed each year (the breath). The histogram allows comparing the different sourcing strategies of the three carmakers especially as regards the external search breath. Furthermore, this graph helps identifying when carmakers started investing in electric batteries, the pick of such investments and the overall trend. Finally, we used the histogram of Sierzchula *et al.* (2012), which represents the "life-cycle" model of battery technologies, to compare and correlate sourcing and technology "life-cycle" models.

4. Findings

4.1 EVs and batteries technology

Electric vehicles debuted in California in 1996. EVs vehicles were the carmakers' answer to new California's state requirements. California legislated the so-called Zero Emission Vehicles (ZEV) mandate, which required major car manufacturers to introduce emission-free power trains for part of their vehicle sales (Bergek, *et al.*, 2013). Following the ZEV mandate, all incumbents launched battery electric cars but none of them produced more than 1,500 units (Mangusson and Berger, 2013). Nevertheless, starting from that experience, several carmakers went on investing in EVs technologies. In 2016 the International Energy Agency (IEA) has published the Global EV outlook on electric cars showing that in 2015 the global threshold of 1 million electric cars on the road has been exceeded, closing at 1.26 million, about the double of 2014. The 2020s is expected to be the decade of EVs. Electric Vehicles (EVs) are of three types: Hybrid Electric Vehicles (HEVs), Plug-In Hybrid Electric Vehicles (PHEVs)[1] and Battery Electric Vehicles (BEVs). Interestingly, hybrids are more complex than BEVs because engineers have to combine the virtues of combustion engines with that of electric drives. Also hybrids require contemporarily managing diverse technologies and the necessity of parallel testing and development. Today, hybrid-electric power trains remain the dominant alternative power train in the global automotive industry. According to recent estimates, HEVs (including plug-in hybrids) could become the dominant vehicle technology in the next two decades, while pure electrics may require extensive policy support until the late 2020s (Schott, Püttner and Müller, 2015). The main reason for this is that hybrids offer key performance advantages in comparison with EVs in terms of driving range, cost, and ease of charging. But all EVs require electric batteries, as opposite to Internal Combustion Engine Vehicles (ICEVs) historically produced by carmakers, and hence constitute a technological discontinuity. For some carmakers this discontinuity led to the development of innovative platforms, for others the new motorizations required the adaptation of existing platforms. Carmakers have so far followed two different strategies. Some carmakers have developed their electric vehicles (EVs) on the same Internal Combustion Engine Vehicles (ICEVs) platforms, such as Ford, Toyota, GM and Renault-Nissan. Others, such as BMW, VW, Tesla and Mercedes-Benz have developed a new electric car

[1] Plug-in hybrid vehicles (PHEV) are a combination of a conventional combustion engine with an electric motor. Depending on the battery size and use, a solely electric propulsion is possible over an adequate distance. Compared to hybrid types, plug-in hybrid vehicles have a more powerful electric traction motor.

platform.

Electric-car batteries consist of modules assembled into battery packs (including an electronic control unit and a cooling system). Batteries and their technology play a significant role in determining technical attributes and performance of EVs. Energy storage devices can be differentiated by type of rechargeable battery. Multiple competing technologies exist, e.g. lead-acid, nickel-metal hydride, or lithium-ion battery. These competing technologies can be compared along six dimensions: safety, life span (measured in terms of number of charge-and- discharge cycles and overall battery age), performance (peak power at low temperatures, state-of-charge measurement, and thermal management), specific energy (how much energy the battery can store per kilogram of weight), specific power (how much power the battery can store per kilogram of mass), and cost (on the business side the challenge will be to reduce manufacturing costs through scale and experience effects). Today no single technology dominates along all six dimensions and several technological trade-offs exist, such as the trade-off between the performance and the safety of a technology.

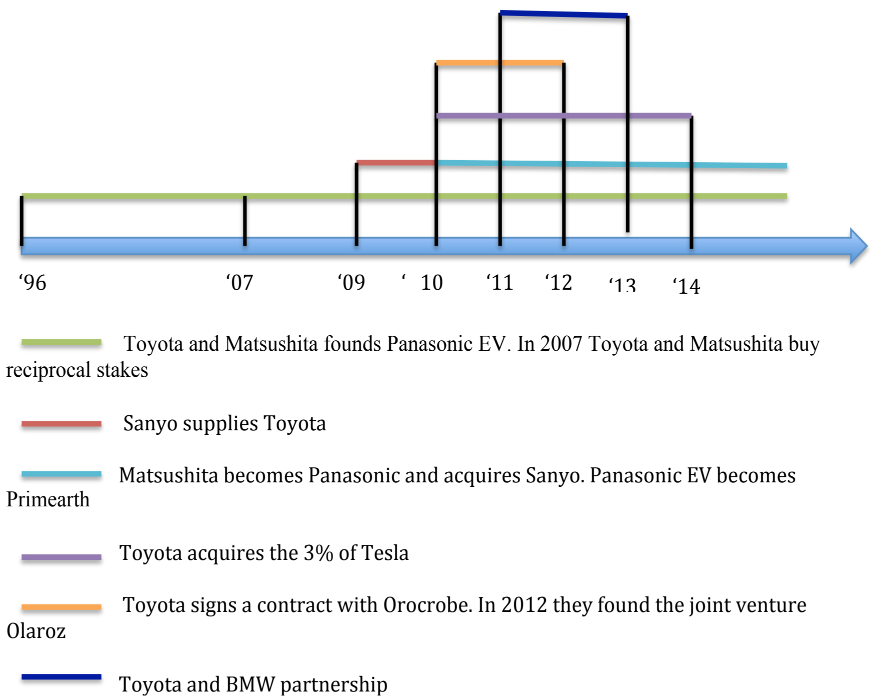
After a period of search and experimentation, in 2011 carmakers heavily converged on lithium technologies because the maximum energy they can generate is higher than that of nickel batteries (Sierzchula *et al.*, 2012). Also, lithium batteries are lighter and smaller because they have a higher recharge density and they dissipate less energy. Furthermore, Li-ion batteries do not display memory effects: batteries can be recharged multiple times before their energy is fully consumed without reducing their storage capacity. Finally Li-ion batteries have a lower rhythm of auto discharge. But lithium batteries have a shorter life-cycle than nickel batteries independently from the number of recharges. Also, when electrified cars employ lithium batteries they also need additional security systems to avoid overheating and explosions. Finally, lithium is available in nature in limited quantities and these batteries are more expensive (Lu, Han, Li, Hua and Ouyang, 2013). Overall, even if today lithium-ion batteries are the most diffused they still comprise a family of battery chemistries that employ various combinations of anode and cathode materials and are still under development (Herrmann and Rothfuss, 2015; Schott, Püttner and Müller, 2015).

4.2 Toyota

Toyota Motor Corporation (henceforth Toyota) is a Japanese carmaker. Toyota also owns Lexus, Scion, Dahiatsu and Hino Motors. In 2014 Toyota sold 10.23 million vehicles in 170 countries and produced them in 28 countries employing more than 338 thousand people all around the world (http://www.toyota-global.com/company/profile/). Figure 2 shows the Toyota's timeline that synthesizes the main partnerships that Toyota activated for the batteries.

Toyota attention toward hybrid cars started during the 90s. In 1996 Toyota and Matsushita Electric Industrial founded Panasonic EV Energy Co. This joint venture, owned by Matsushita Electric Industrial for the 60% and by Toyota for the 40%, invested in R&D activities and produced nickel metal-hydrate (Ni-Mh) batteries. At the end of 1997 Toyota launched the first hybrid model, the first generation of Toyota Prius, which sold about 160 million vehicles all around the world (http://www.greencarcongress.com/2007/06/toyota-and-mats.html). So Toyota became a significant mass producer of electric motors and engaged in intimate collaboration with its supplier of electric vehicle batteries, Panasonic, to develop hybrid-electric battery systems to be integrated in the hybrid power train. The companies formed a joint venture and during the development project Toyota located a significant number of vehicle engineers at Panasonic. At a later stage, Toyota acquired a controlling interest in this joint venture. In 2003 Toyota launched the second generation of Prius. Technological improvements allowed increasing the size of Prius and its autonomy and efficiency. The batteries were still produced by Panasonic EV Energy. In 2005 Toyota increased its participation in Panasonic EV Energy till buying the 80.5% of shares. Toyota heavily invested in Panasonic EV Energy and triplicated the production capacity of the Miyagi plant investing about 300 million dollars. These investments were necessary to cope with the market success of the Prius (http://www.greencarcongress.com/2010/03/tmc-20100330.html). In 2007 Toyota and Matsushita Electric Industrial reinforced their partnership: Toyota acquired 20.7 million shares in Matsushita (http://www.industryweek.com/companies-amp-executives/toyota-boosts-ties-matsushita). In 2008 Matsushita Electric Industrial changed its name in Panasonic (http://news.panasonic.com/press/news/official.data/data.dir/en081001-4/en081001-4.html). In 2009 Toyota decided to switch from a single sourcing strategy to a double sourcing strategy starting a new supply relationship with Sanyo for the supply of lithium batteries (Berman, 2009; Fallah, 2010). At the end of 2009 Panasonic completed a 400 billion yen acquisition of a 50.2% stake in Sanyo, making Sanyo a subsidiary of Panasonic. In 2010, Panasonic announced that they would acquire the remaining shares of Sanyo (Wakabayashi, 2010).

Fig. 2: Timeline of the main Toyota's partnerships for the production of batteries



Source: Our elaboration

In 2010 Toyota bought the 3% of Tesla Motors and signed a contract with Orocobre. Tesla is a Californian firm founded in 2003 that produces electric vehicles. Orocobre is a mineral firm, which headquarter is in Australia, specialized in the extraction of lithium and boric compounds. Orocobre has invested in an extraction project in Argentina that enables the firm to extract 16000 high quality tons of lithium a year at competitive costs. In 2012 Toyota enters in a joint venture with Orocobre and the two firms found Olaroz. Toyota owns the 25% of Olaroz (http://www.orocobre.com.au/Projects_Olaroz.htm). In 2011 Toyota and BMW signed a "memorandum of understanding" to jointly develop the next generation of electric lithium batteries. The technologies jointly developed have been applied in BMW in the models i3 and i8, while Toyota is going to use them for the Prius. These new batteries have a longer duration and a higher power than the nickel metal-hydrate (Ni-Mh) batteries. In 2011 Toyota invested other 60 million dollars in the relationship with Tesla; the agreement was to jointly develop the RAV4, a plug-in electric vehicle. For Toyota this is the first full electric vehicle. The project combines the Tesla knowledge of electric cars technology with the Toyota production and distribution capacity (http://www.teslamotors.com/it_CH/forum/forums/tesla-signs-60-mln-deal-toyota-develop-electric-version-rav4). But in 2014 Toyota, after three years and several million dollars invested, decided to end this partnership. Several may be the causes of this decision: the RAV4 failure, the Toyota focus on hybrid and hydrogen cars, or the Tesla strategy aimed at opening its technology (Quinn, 2014; Volkman, 2014). In 2014 Primearth (the new name of Panasonic EV from 2010) has increased the production of nickel metal-hydrate (Ni-Mh) batteries to satisfy the demand of Toyota hybrid cars.

The Miyagi plant will be expanded to supply 500 million cars a year, 200 millions more than the cars today produced (http://economictimes.indiatimes.com/auto-technology/toyota-subsidiary-to-expand-hybrid-car-battery-production/articleshow/38424116.cms).

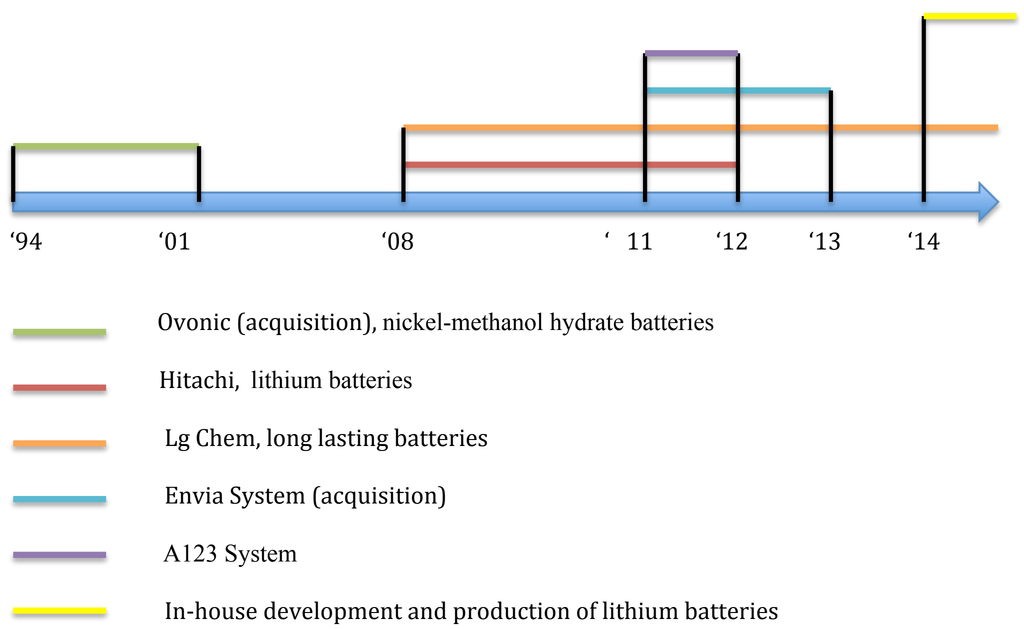
Overall, Toyota in 2014 still invested in both nickel metal-hydrate (Ni-Mh) and lithium batteries mainly through its joint venture and reciprocal investments with Panasonic, a first tier supplier.

4.3 General Motors

General Motors (GM) is a US firm whose headquarter is in Detroit (Michigan). GM owns ten brands: Opel, Cadillac, Chevrolet, GMC, Holden, Vauxhall Motors, Buick, Auto Baojun, Wiling Motors and Fawjiefang. GM sells his products in 157 countries and produces his vehicles in 37 countries employing more than 219 thousand people all round the world. GM is the third carmakers for global sales in 2014 with 9.924 million vehicles and he is the leader in the light vehicles segment (http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2015/Jan/0114-gm-2014-global-sales.html). Figure 3 shows the GM's timeline that synthesizes the main partnerships that GM activated for the batteries. In 1994 GM acquired Ovonics, which produces batteries and it is owned by Ovshinsky the inventor of the modern nickel-methanol hydrate battery (Ni-Mh). GM and Ovonics founded the joint venture GM Ovonic (Wald, 1994). The original aim of this acquisition was to control the development of the Ni-Mh technology for the first GM electric car, the EV1 BEV. Nevertheless, GM had to face the action of the US Auto Battery Consortium (USABC), which was willing to pursue the interest of the carmakers belonging to the consortium by limiting the development of the Ni-Mh technology. Indeed, GM decided to renounce to his project and in 2001 the oil company Texaco acquired the GM's share of Ovonics (http://en.wikipedia.org/wiki/Who_Killed_the_Electric_Car%3F). In 2008 GM started producing the Chevrolet Malibu hybrid, which embodies the batteries produced by Cobasys (http://www.cobasys.com/news/20070313.shtml). During the same year GM and Hitachi, a Japanese firm leader in the electronic and electric industry, signed an agreement for the supply of lithium batteries to be installed on more than 100.000 cars produced by GM (http://www.hitachi.com/New/cnews/080304.html). The 2008 is a very dynamic year: GM announced a project with LG Chem Ltd to develop long lasting batteries. LG Chemical is the biggest Korean chemical company and operates in the battery industry through a subsidiary, the Compact Power. LG Chem started supplying GM for the full electric version of the Chevrolet Volt and in 2010 LG started supplying GM also for the new Chevrolet Cruze (http://www.reuters.com/article/2008/10/22/gm-volt-idUSN2239779020081022).

In 2011 GM invested more than 17 milion dollars in Envia Systems, with the aim of reducing of about one third the final cost of the electric vehicles and to create batteries able to supply 400 watt-hour per kilo (the Tesla batteries supplied a maximum of 130 watt-hour per Kilo) (Ingram, 2013). Also, in 2011 GM enlarged its partnership with LG to the design and production of a large set of components for electric vehicles and they realized the new structure of the cathode of the Li-ion battery (http://www.greencarcongress.com/2011/08/gmlg-20110825.html). The same year GM presented two new car models that rely on the Li- Ion batteries supplied by Hitachi: the hybrid model Buick LaCrosse and the electric model Chevrolet Volt. The Chevrolet Volt has the motor, invert and batteries all supplied by Hitachi (Greimel, 2011). In 2011, GM starts a partnership with A123 System, which is a chemical firm founded within the MIT. The partnership is mainly focused on the co-developed of the software to control the batteries (Cobb, 2012). Il 2012 the new Buick Ragal embodies the Hitachi Li-Ion batteries. This will be the last model produced with the Hitachi technology. The main reason of this departure is the Hitachi strategy: the firm aims at becoming a global supplier without having close relationships with specific carmakers. During the same year GM ended also the collaboration with A123 System, which will be acquired by the Chinese Auto Industry Wanxiang Group. In 2013 GM launched the EV Spark with the Nanophospate Li-Ion batteries developed with A123.In 2013 GM ended its partnership with Envia that was not able to meet the GM's expectations (Ingram, 2013). In 2013 also GM presented the new Volt with LG batteries. The relationship between GM and LG is stable and GM invests 449 million dollars to produce electric vehicles with LG. (http://cleantechnica.com/2013/08/09/lg-chem-plant-to-make-american-batteries-for-chevy-volt/).

Fig. 3: Timeline of the main GM's partnerships for the production of batteries.



Source: Our elaboration

Indeed, GM is investing in lithium batteries and in an exclusive partnership with LG Chem. But in 2014 GM announced that General Motors Co. is moving production of the battery pack for its all-electric model of the Chevrolet Spark minicar in-house at the company's battery assembly plant in Detroit. The pack was previously supplied by A123 Systems. GM is going to invest $65 million to expand the production of lithium-ion batteries. Larry Nitz, executive director of GM global transmission and electrification engineering, said in a May 14, "Using our in-house engineering and manufacturing expertise enabled us to deliver a battery system that is more efficient and lighter" (http://www.plasticsnews.com/article/20140515/NEWS/140519948/gm-bringing-more-lithium-ion-battery-production-in-house). In 2014 LG Chem announced that they would supply also VW and the Audi brand (http://www.greencarreports.com/news/1085827_battery-maker-lg-chem-biggest-electric-car-winner-of-all).

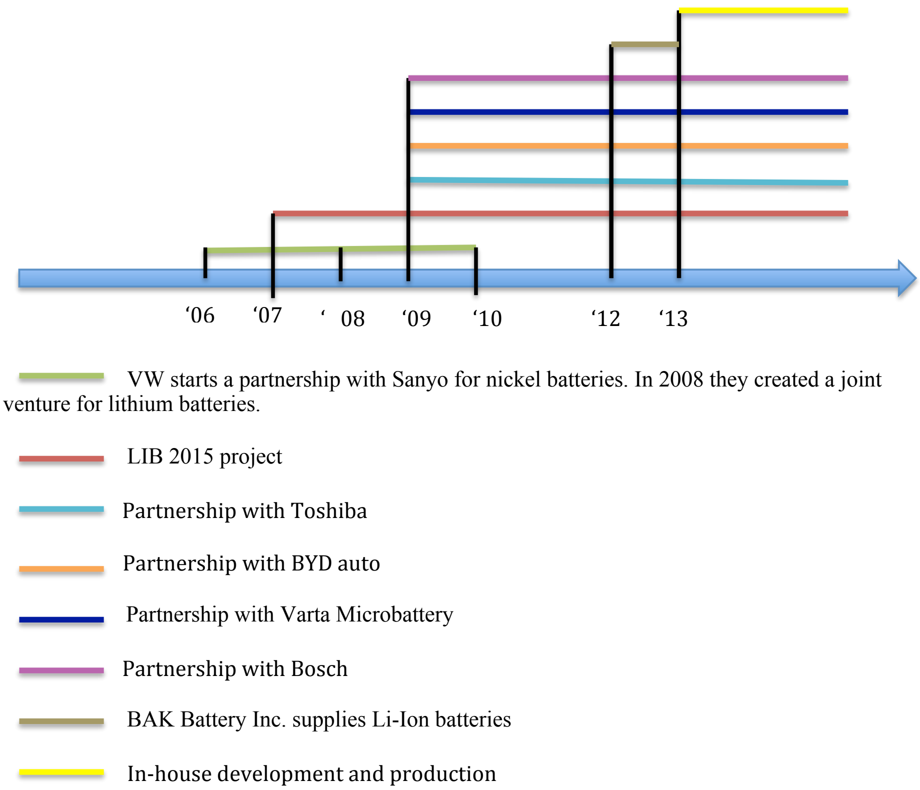
Overall, GM entered in multiple supply relationships, more or less tighten, with a number of first tiers and one component supplier. At the end of 2014, GM relied on lithium technology, one first tier supplier and on a concurrent sourcing strategy.

4.4 Volkswagen

Volkswagen Group (henceforth VW) is controlled by the holding Volkswagen AG, which headquarter is in Wolfsburg (Germany). The holding owns several car brands: Audi, Lamborghini, Bentley, Bugatti, Porche, Seat, Skoda, Scania AB, MAN SE and Volkswagen.

VW is the main European carmaker and the second worldwide in 2014 with more than 10.14 million vehicles sold in more than 150 countries. VW produces in 27 countries and employ more than 550 million people (http://www.volkswagenag.com/content/vwcorp/content/en/the_group.html). Figure 4 shows the VW's timeline that synthesizes the main partnerships that VW activated for the supply of batteries.

Fig. 4: Timeline of the main VW's partnerships for the production of batteries.



Source: Our elaboration

VW started investing in the electric/hybrid niche only in 2006 with a partnership with Sanyo to develop nickel batteries. Sanyo was not yet entered in the Toyota-Panasonic relationship (http://www.greencarcongress.com/2008/05/vw-and-sanyo-fo.html). In 2007, VW participated to an R&D project named LIB 2015 (Lithium Ion Battery) (http://www.isi.fraunhofer.de/isi-en/t/projekte/at-lib-2015-roadmapping.php) sponsored by the government and aimed at increasing the performance and sustainability of lithium batteries. The project involves several firms such as BASF, Bosch, Evonic Deguessa and Li-Tec. The hybrid model Audi A1 presented in 2007 embodies the technologies developed during this project. In 2008 Sanyo started supplying also lithium batteries to VW and they created a joint venture (Chang-Ran, 2008). In 2009 VW empowered its relationships with the suppliers of batteries. VW signed a letter of intents with Toshiba to join their technologies to develop more efficient electric propulsions and batteries with a higher energy density (http://www.volkswagen.co.uk/about-us/news/128). The same year VW and the Chinese BYD Auto signed an agreement for the co-development of hybrid and electric cars with a Li-Ion technology. The BYD Auto is a subsidiary of the BYD group, which is the global leader of the production of Ni-Cd batteries and of mobile batteries. The partnership was supposed to improve VW knowledge of batteries and to help BYD entering the automotive industry as carmaker (Kaufmann, 2009). In 2009 VW also signed a partnership with Varta Microbattery: Varta would have shared his know-how about batteries and accumulators with VW with the aim of increasing batteries performance and VW would have ensured a large purchase of batteries (http://in.reuters.com/article/2009/09/25/us-volkswagen-varta-idUSTRE58O2KN20090925). But VW went on searching further partners and monitoring the market. For example VW shared information with Bosch-Samsung JV and LG Chem. Particularly VW believes that the Japanese carmakers have batteries more performing than that produced by BYD (Doggett, 2010).

In 2010 VW ended its supply relationship with Sanyo, which has been acquired by Panasonic, a partner of Toyota. The same year VW presented the first model of hybrid SUV, the Tuareg Hybrid, for the EU market. The batteries are Ni-Mh batteries produced by Bosch. In 2012 VW started purchasing Li-Ion batteries from the Chinese BAK Battery. VW aim was to test these batteries on some models to evaluate their performance. But this relationship did not go on (http://www.bak.com.cn/news_detail.aspx?NewsCateID=21&CateID=21&NewsID=790). In 2013 VW presented two new electric models: the e-Up! and the e-Golf. Both models have lithium batteries. The motor, gear and batteries are all developed produced in-house. Furthermore, VW announced that he is going to increase investments in electrified motorizations and also in the batteries technology (http://www.greencarcongress.com/2013/09/20130911-vw.html).

Overall VW purchased batteries from multiple first tier suppliers but also had as partners one carmaker. At the end of 2014 VW was investing directly in lithium batteries technology and production.

4.5 Toyota, GM and Volkswagen's supply chain strategies comparison

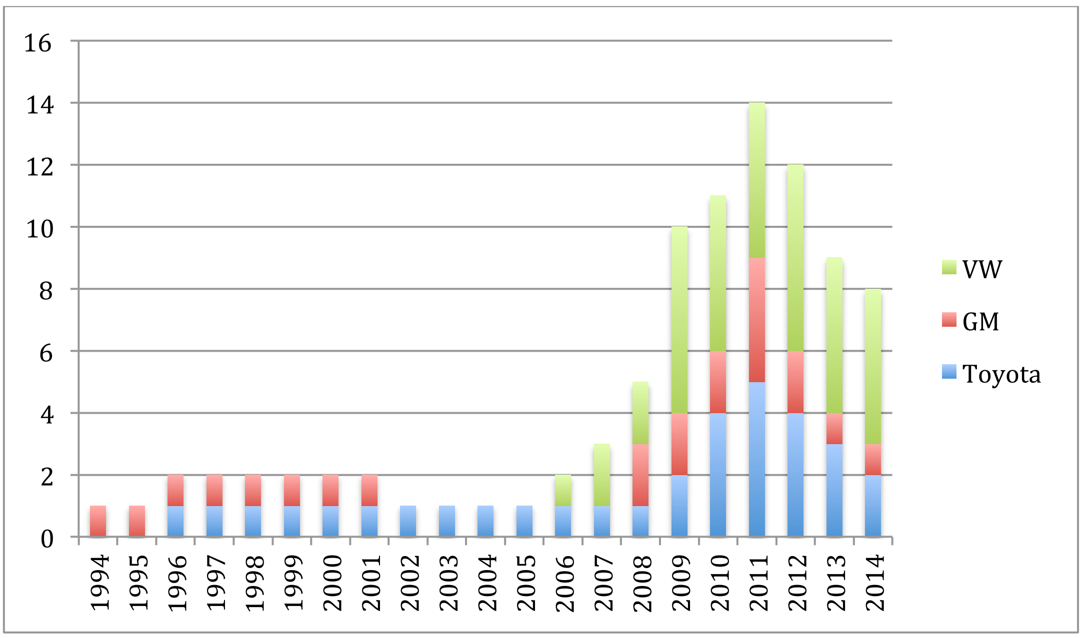
The histogram represented in Figure 5 shows the number of relationships for each carmaker from 1994 to 2014. VW entered the market when the other OEMs started heavily exploring new partnerships.

All the analyzed carmakers contemporarily increased the number of their partnerships and investments for batteries in 2008 with a pick in between 2010 and 2012. Interestingly this is the period during which lithium became the widespread dominant chemistry used in batteries. "The period of 2008–2011 saw an increase in the number of EV models using lithium batteries and a decrease in the use of all other battery chemistries. This indicates that EV manufacturers have determined that lithium batteries represent the best opportunity for EVs to be competitive in the automobile industry" (pp. 58, Sierzchula *et al.*, 2012).

In 2014, all the three analyzed carmakers mainly focused on lithium technology.

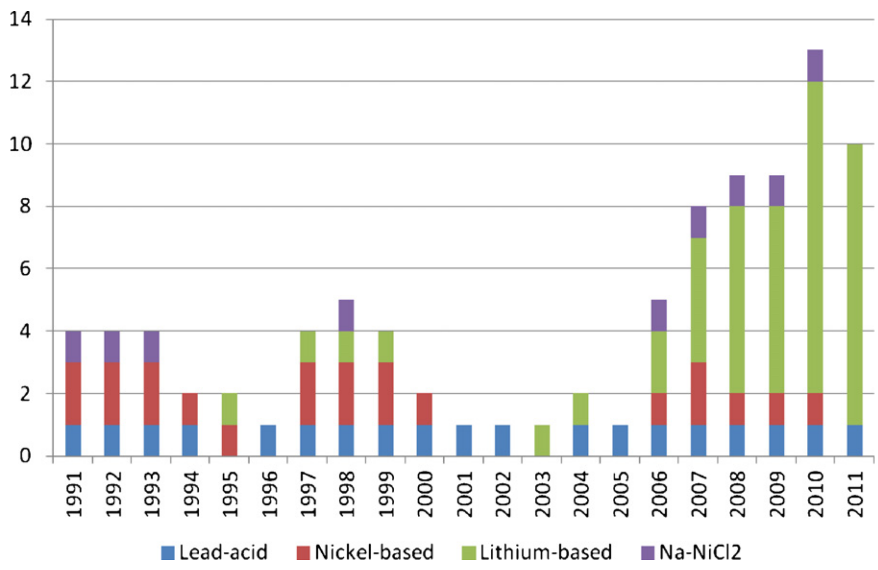
Sierzchula *et al.* (pp. 58, 2012) provide the Abernaty and Utterbach curve for the number of unique battery chemistries used in EV models from 1991 to 2011 (see figure 6). This number shows a trend overlapping with Figure 5 thus suggesting a tight correlation between technological discontinuities and incumbents sourcing strategy: the higher the technological turbulence the higher the incumbents exploration of the technological landscape through multiple strategic alliances. Both curves have an inverted u-shaped relationship.

Fig. 5: Number of partnerships that the three carmakers managed from 1994 to the end of 2014



Source: Our elaboration

Fig. 6: Number of unique battery chemistries developed from 1991 to 2011



Source: Sierzchula *et al.* 2012, page 58

Figure 6 shows that carmakers started increasing sharply the number of batteries technologies and particularly lithium technologies since 2006 and they contemporarily increased the breath of their open innovation search strategy. This period of high investments in batteries technology lead to significant improvements in lithium-ion technology and a decrease in the number of battery chemistries produced. Uncertainty about dominant technology is reduced after 2011. Figure 5 also shows that after 2011 the number of suppliers decreased and the three carmakers started selecting the partners with whom to collaborate: Toyota confirmed his relationship with Matsushita, GM consolidated his relationship with LG Chem. VW, the later entrant, still maintained multiple partnerships. Correlation between data in Figure 5 and 6 is stronger for Toyota and GM that had a longer experience in EVs.

Overall the three OEMs approached batteries technology with one main partner and then faced a period of exploration in which they added further suppliers, partners and technologies. Often these partnerships were strategic alliances aimed at improving and at exploring different battery technologies. Then, Toyota and GM confirmed their initial main supplier increasing the strength of this relationship, while VW, who entered later, is still exploring multiple partners. Furthermore, when a dominant technology emerged, both GM and VW started developing and producing batteries in-house.

5. Discussion and conclusions

Despite the differences in the timing of entry of the analyzed carmakers, they relied on a similar sourcing strategy characterized by three steps. First, carmakers gradually approached batteries technology by selecting one main partner with whom they had a long lasting relationship. In all three cases the selected supplier was a big industry player. Hence carmakers built gradually a knowledge base about batteries technology and subsequently this knowledge base allowed managing a higher number of partners and multiple different technologies and projects. We label this first step the "absorptive capacity" step during which OEMs acquired the basics of electric batteries (Cohen and Levinthal, 1990).

Second, carmakers started signing and entering in multiple partnerships, mainly strategic alliances, coherently with the high technological dynamism of this niche: all carmakers experimented multiple suppliers, partners and technologies in search for the most performing solutions. As Grant and Baden-Fuller (2004) argue the primary advantage of alliances over market is in accessing and applying knowledge. Alliances let carmakers explore and access to additional and new complementary competences. Alliances contribute not only to the acquisition of new knowledge but also to the efficiency in the application of knowledge (Brown and Eisenhardt, 1997; Kogut, 1991; Kogut and Kulatilaka, 1994). In this study joint ventures, co-ownerships and concurrent sourcing are the supply chain management models most used by carmakers. These relationships, and the carmakers knowledge base, are also nurtured by other shorter supply relationships (with components suppliers and competitors) aimed at exploring new technologies.

During the third phase carmakers, after having explored multiple technologies via multiple partnerships, focused on big and few first tiers to develop and apply the selected technologies. Carmakers first explored multiple technologies and then exploited them via selected partnerships. This third phase corresponds to lower levels of technological dynamism, uncertainty and to the predominance of lithium technology. The first and second phases also allowed acquiring the competences needed to start producing in-house batteries during the third phase. The tight control over few selected suppliers and the concurrent sourcing strategy are both coherent with the relevance that electric batteries have for EVs.

These three steps describe an inversed U-shaped model (see Figure 5) that resembles the Abernaty and Utterback product life cycle (1978) in Figure 6. The product life-cycle model is graphically illustrated as a hilly curve representing the frequency of product innovations that flats when a dominant design emerges. Our study shows that incumbents lacking core competences about the new discontinuous technology employ a U-shaped sourcing strategy in which the number of relationships has a pick when carmakers explore multiple technologies and then goes down when a dominant technology arises.

Our findings are also in line with, and suggest a dynamic interpretation of, the Laursen and Salter (2006) model of firms' external search strategy. The authors suggest that organizations often have to go through a period of trial and error to learn how to gain knowledge from an external source. During this process of learning firms learn how to absorb further external knowledge. This is the first step of our model in which carmakers create absorptive capacity through few partners. Secondly firms can manage a higher number of partners and explore further the technological landscape till uncertainty is reduced. When technological uncertainty is reduced firms are better-off limiting their external search breadth. Using Laursen and Salter own-words "firms may 'over-search' and this will have negative consequences for their innovation performance" (pp.135, 2006). Over-searching may have a negative influence on performance because firms may have too many ideas to manage, ideas may come at the wrong time and in the wrong place to be fully exploited and few of these ideas can be taken seriously or given the required level of effort. Hence there is a point at which external search breadth becomes disadvantageous. In sum, external search breadth is curvilinearly (taking an inverted U-shape) related to innovative performance. Our data suggest that this inverted U-shape relationship may be also depicted as a learning process through which firms create a knowledge base, explore the environment and retain selected partners.

Also this paper contributes to supply chain management literature by describing how incumbents rely on external partners and how they approach evolve in time with the technology. EVs' performance heavily depends on batteries: the distance covered with a recharge, the recharge time, the price, the consumption and efficiency. This explains why OEMs, willing to enter in this market niche, opted for strict partnerships with suppliers and invested to improve the technology of batteries. Furthermore, today carmakers outsource the most of the car's components to specialized suppliers but they still retain core competences and production capacity about car's motorization: this may explain why they are interested in maintaining a high control also over electric motorizations. This is why they engage suppliers in close partnerships through which exchange knowledge and information and have also started producing batteries in-house.

Moreover, batteries have to be designed to suit specific car models and thick/long lasting relationships with suppliers favor complex design activities aimed at including batteries into cars architectures. In fact, as previous studies suggested, even in case of incremental/modular innovations, carmakers cannot simply plug-in the modular component into the car architecture. Carmakers need to maintain the control over the car architecture and integrate the new components via hand-in-glove relationships with suppliers through which exchange data and information about the components to integrate (Brusoni and Prencipe, 2001; Cabigiosu, 2013; Furlan *et al.,* 2014).

Automakers are highly involved in the design and production of batteries for their vehicles. As GM observed, "the Volt's battery pack design is directly coupled with the vehicle design to assure complete integration between the battery pack and the vehicle." This means that the automaker's decision about which batteries to buy, and the supplier to involve, will be in effect for a prolonged period, perhaps the life of the vehicle model, as a battery designed for one vehicle may not function optimally in another. This dependency over suppliers may favor control or concurrent sourcing strategies (Parmigiani, 2007).

Our findings about VW and GM are also in line with Parmigiani (2007) who suggests that in times of technological change, concurrent sourcing may offer increased learning by combining internal and external knowledge streams. Also, concurrent outsourcing may help firms facing variable volumes of sales by adapting their production capacity, it may improve suppliers' benchmarking or generate economies of scope. Similarly, our findings about the choice of a concurrent strategy are in line with Brusoni and Prencipe (2001) who suggest that firms need to make in order to know and effectively design complex systems.

Hence the paper also contributes to the modularity literature by supporting the mirroring hypothesis in the case of integral products: batteries are supplied via tight relationships with suppliers and/or concurrent sourcing strategies coherently with the integrality of the components supplied. Battery packs are developed to fit specific car models and constitute an idiosyncratic investment, especially for those carmakers that develop dedicated EVs platforms. Hence battery packs cannot be easily standardized and sold as modules by big suppliers via market-based transactions (Cabigiosu and Camuffo, 2012; Colfer and Baldwin, 2016).

This study also emphasizes the relevance of the most recent contributes about modularity and the mirroring hypothesis that ask for a contingent view of the mirroring in which technological uncertainty is central in shaping sourcing strategies (Furlan *et al.,* 2014).

Finally, the study also has practical implications by offering a representation of how supply relationships evolve in turbulent environments especially when technology is uncertain. Managers can rely on the "life-cycle" model of sourcing strategies to plan and analyze their portfolio of partners depending on the level of technological uncertainty.

Even if this paper has the merit to extend existing knowledge about the incumbents' sourcing strategies during technological discontinuities, future studies may enlarge the sample including leading players in this niche market, such as Nissan, and offer a more in-depth explanation of the strategic reasons behind suppliers' choice and relationships mode of governance. Also primary data and focused interviews may increase our understanding of how and why OEMs pursued specific sourcing strategies. Finally, future studies may look at the most recent incumbents' choices as regards sourcing and technology strategies.

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