Relations between battery suppliers and automakers for knowledge base development during paradigmatic shifts in technology

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Abstract: In this paper, integrators' and suppliers' relative focus on component versus architectural knowledge during a potential paradigmatic shift in technology is studied, using the electrification of the vehicle's powertrain as a case. US patents granted to six automakers and two of their battery suppliers during the period 1976 – 2009 form the main empirical basis. The study provides empirical support for an increasingly important role of batteries in the vehicle's powertrain and illustrates the wide variety in knowledge development approaches of the automakers and battery makers. In relation to previous literature, this paper details the terminology used in relation to the component and architectural dimensions, it investigates the knowledge overlap in relation to the degree of uncertainty and it proposes additional factors potentially related to the knowledge strategies.

Keywords: Knowledge partitioning, inter-firm relations, battery, electric vehicle, paradigmatic shift.

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1 Introduction

By definition, a paradigmatic shift in technology implies a need for a new knowledge base (Hill and Rothaermel, 2003). Furthermore, a paradigmatic shift might make core knowledge obsolete, a process termed “creative destruction” by Schumpeter. Incumbents’ difficulties in handling paradigmatic changes are highlighted in several studies (Christensen, 1997; Cusumano et al, 1997; Tripsas and Gavetti, 2000) and even “[t]echnology and resource-rich firms often fail to compete in the very technologically turbulent environment that they helped to create.” (Tushman et al, 1997:3) To stay competitive, the firm has to adapt its knowledge base, a process which calls for an evolutionary learning capability, as argued by Fujimoto (1999) amongst others.

Inter-firm relations may facilitate rapid learning and increase the ability of the firm to innovate (Powell et al, 1996). Furthermore, they contribute to keeping the firm informed (Gibbons et al, 1994) and network resources have a significant influence on firm performance (Dyer and Hatch, 2006). One strategically important issue for management to handle is the balance between firm-internal and firm-external knowledge accumulation (Takeishi, 2002). The standard division is that the integrator focuses on architectural and the supplier on component knowledge. In periods of uncertainty, it is argued that the need for an overlap in knowledge is greater (Lee and Veloso, 2008; Takeishi, 2001; 2002; Zirpoli and Camuffo, 2009). However, the Lee and Veloso (2008) study indicates that the trend towards increasing component innovation over the product life cycle dominated over the uncertainty effect for integrators.

The main ambition of this study is to discuss integrators and suppliers development of component and architectural knowledge in relation to a potential paradigmatic shift in technology. Empirical data is drawn from the automotive industry and the potential shift to electric propulsion. In this shift, the development of a tractionary battery knowledge base is specifically addressed. Six large automakers’ relationships to battery makers since the mid 1990s were investigated and the patenting activity of auto and battery makers for the period 1976 - 2009 was studied so as to obtain an indicator of the knowledge accumulation. As a part of the patent search strategy, a total of 3,033 patent records were manually scrutinised to check their relevance and classify them.

There have been several studies of inter-firm relations in the automotive industry (e.g. Clark and Fujimoto, 1991; Dyer and Nobeoka, 2000; Liker et al, 1996) with some specifically addressing the development of the knowledge base (e.g. Lee and Veloso, 2008; Takeishi, 2001; 2002; Zirpoli and Becker, 2009). This study differs as it addresses only one technology as central to a potential paradigmatic shift. Since there is a dependency between the component or knowledge being supplied and the type of firm-external relations (Liker et al, 1996), it can be argued that a specific study of one technology makes a contribution, since an aggregate study of several technologies or components risks missing or blurring important differences. Furthermore, as previous research argues that the type of firm-external relations depends on the newness of the technology it is thus relevant to take a closer look at one technology and application new to the automotive industry, even though battery electric vehicles have actually been around as long as internal combustion ones (Höyer, 2008).

The patent study indicates a rapidly increasing tractionary battery knowledge base. Compared to previous literature on inter-firm relations and knowledge partitioning, when addressing innovative core technologies, this paper provides a more detailed and partly contrasting message regarding the overlap in component and architectural knowledge between integrators and suppliers and it suggests additional factors which may influence firms' knowledge strategies.

The remainder of the paper has the following structure. Firstly, there is a review of literature dealing with paradigmatic shifts in technology, knowledge base development and inter-firm relations. The subsequent section presents the methodology of the study, followed by the empirical data divided into two sub-sections; one describing the relations between auto and battery makers and one summarising the results of the patent study. The results are then discussed in relation to the literature. Finally, there are the conclusions.

2 Theoretical framework

Paradigmatic technological changes imply periods of major uncertainty (Kline and Rosenberg, 1986) and tremendous challenges for the incumbent firms, which often fail to benefit by such changes (Christensen, 1997; Cusumano et al, 1997; Tripsas and Gavetti, 2000). During the process of a paradigmatic change, several technological alternatives often compete (Tushman et al, 1997). Among them, the 'old' technologies often improve significantly; the so-called sailing-ship effect (Pistorius and Utterback, 1997). For firms to stay competitive during such turbulent conditions, several authors emphasise organisational learning (e.g. Cohen and Levinthal, 1990; Kogut and Zander, 1992; Spender, 1996).

One role of in-house research is to enhance opportunities for understanding the technological development (Cohen and Levinthal, 1990). It might also serve as an entry ticket to those networks where new knowledge and ideas are generated (Powell et al, 1996). As most innovations are new combinations of existing technologies (Henderson and Clark, 1990), the establishment of new or stronger relations with external firms is often a quick way of increasing the knowledge base (Powell et al, 1996).

Coase (1937) discussed the boundaries of the firm and later Williamson (1991) used the transaction cost perspective as one framework to address this issue. Uncertainty increases the transaction costs, thus providing an argument for increased vertical integration. Wolter and Veloso (2008) argue that whereas empirical results support this relation as regards demand uncertainty and especially asset specificity, the influence of technological uncertainty is unclear. Addressing this issue, they propose that firm exogenous incremental innovations imply no change in the degree of industry integration whereas architectural innovations lead to increased integration. The consequences of modular and radical innovations are less predictable, but the authors guess that modular ones lead to a decrease and radical ones to an increase in industry integration.

There is often a similarity between the technical and organisational architecture at successful firms (Henderson and Clark, 1990) and MacDuffie (2008) proposes that modular organisations with extensive outsourcing and vertically integrated organisations are the conceptual endpoints in organisational architecture. Long-term supplier relationships such as the Japanese keiretsu lie in between. When outsourcing, Takeishi (2002) argues that one method of handling the risks associated with not having all activities in-house is to differentiate between task and knowledge partitioning. Whereas a supplier dependency on capacity (task partitioning) implies one type of risk, a dependency on knowledge (knowledge partitioning) implies another potentially more important one.

Henderson and Clark (1990:10-11) "define innovations that change the way in which the components of a product are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched, as 'architectural' innovation. [...] A component is defined here as a physically distinct portion of the product that embodies a core design concept (Clark, 1985) and performs a well-defined function." The choice of one design concept to perform the task establishes a core concept of the design (Henderson and Clark, 1990).

In the automotive industry, inter-firm relations "have the potential to reduce fixed costs, to increase flexibility, and to allow learning from other organizations, thus enhancing firms' innovation capabilities." (Lee and Veloso, 2008:419) On the negative side, close relations with suppliers in the product development stage may lead to reduced independency (Womack et al, 1990), difficulties in developing truly new and unique products (Liker et al, 1996) and reduced opportunities for using conventional purchasing procedures to minimise the cost of components supplied (Clark and Fujimoto, 1991). In a study of collaborative projects in the Japanese automotive industry, Takeishi (2001) found that in regular projects, automakers only need cover architectural knowledge and suppliers only component knowledge. However, in innovative projects, component-specific knowledge is also more important for automakers. He suggests this overlap in knowledge should be mutual in innovative projects. In another paper, he argues that an automaker's investment in component-specific knowledge can enable a quick evaluation and use of the new component technology when it becomes available (Takeishi, 2002).

Lee and Veloso (2008) conducted a study of patenting related to exhaust pipe emissions control and compared different periods of relative stability in terms of legal requirements with periods when requirements changed. Their study provides empirical evidence of an increased overlap in knowledge in periods of greater uncertainty. Further, they argue for a life-cycle effect, with a predominance of architectural innovations before the emergence of a dominant design and thereafter a dominance of component innovations for both integrators and suppliers. These life-cycle effects dominate over uncertainty effects for automakers. Finally, their study implies that "expanding the task boundary is especially important when firms are developing systems and technologies that are relatively new to their existing product base. Thus, to succeed in technological races, assemblers and suppliers may need to develop internal R&D capabilities more aggressively in areas beyond their existing and even future production domains." (Lee and Veloso, 2008:431)

In summary, previous literature argues that inter-firm relations are important for several reasons, not least when facing potential technological shifts. The degree of vertical integration and overlap in knowledge depends on several factors, among them the product architecture, the level of uncertainty and the phase in the product cycle. Basically, modular product architecture and low uncertainty relate to low vertical integration and limited overlap in knowledge. Furthermore, increasing focus on component knowledge is a trend over the product cycle.

3 Methodology

The basis for this study is patent data from the US Patent and Trademark Office, public domain information from firms and media and contacts with battery experts. The study was limited to six automakers plus battery makers with relations to these six in the last two decades. This selection was because: these six automakers were all directly addressed by the Californian Zero Emission Vehicle Mandate at the start of the 1990s (Anderman et al, 2000); they have all been active on a global market and in particular the US one; they have all developed and produced a wide range of different vehicle types; and they have all been among the largest automakers in the world even though their relative positions have shifted over time. Relations between auto and battery makers were investigated using a combination of a large number of different sources, each providing one or more facts to this semi-confidential type of material. Interestingly, even though the battery is a new and crucial part of a hybrid electric vehicle, automakers do not provide very much information about it; sometimes not even the name of its manufacturer. Some direct contact with automotive analysts and engineers at automakers was made in order to obtain complementary data and verify findings.

Granted patents are the outcome of a rigorous process, whereas patent applications are only in the final review process. Approximately two thirds of US patent applications are granted (Griliches, 1990). Consequently, granted patents form a more solid basis for analyses than patent applications. US patent data was used for this study as it can be argued that the use of one single patent database facilitates a fair comparison (Freeman, 1987). However, the choice of the US database might introduce a bias, since patenting in the home market is preferred (Watanabe et al, 2001). Among the six automakers studied, three have their headquarters and the majority of their R&D in the US. Another obvious potential source of bias is firm size. A large firm can be expected to have more resources and file more patents. One approach to correcting this type of bias could be to normalise patent volumes in relation to sales volumes for each period. Neither home market nor size-related effects have been compensated for in this study.

As argued by Dosi (1982) amongst others, there is a significant correlation between R&D efforts and innovative output as measured by patenting activity. Griliches (1990) emphasises two major problems in using patents for economic analysis: intrinsic variability and classification. The intrinsic variability or the value of patents can be estimated by investigating the share of patents considered worth the renewal fees. This might apply to general studies but was not considered to contribute much to this study. One way to avoid this type of bias is to study the share of a certain type of patents compared to the total number granted to a firm or a group of firms. This study presents results using this approach.

As regards the classification issue, a search strategy was developed according to the following. Patent classes and keywords to sort out ‘battery-related’ patents were identified using input from experts as well as an iterative procedure starting by a large number of patent classes and keywords, which were tested one by one against a large sample of more than 100,000 ‘automotive’ patents (defined by the patent classes 180 Motor vehicles, 903 Hybrid electric vehicles (HEVs), the keywords automotive and automobile and the patents assigned to the six automakers in this study). Among them, the ten with the highest number of hits were then tested to determine their respective unique contribution to the total sample obtained by all ten patent classes or keywords, in order to reduce the number of keywords (the USPTO database has limitations in terms of the allowable length of the search string). In Table 1, the top-ten keywords and their respective unique contribution to the total sample are presented. Three patent classes and two keywords, which covered 97.5 percent of the sample, were selected (in italics in Table 1) and then used to search for each actor’s ‘battery-related’ patents. One closely related technology is fuel cells and patent records with ‘fuel cells’ in the abstract or title were therefore explicitly excluded from the sample.

Table 1: Keywords and patent classes

Subject	**n**	**Delta (unique contribution)**
Battery/batteries	*3,443*	*2,260*
Electrode	*1,886*	*1,033*
Class 429: CHEMISTRY: ELECTRICAL CURRENT PRODUCING APPARATUS, PRODUCT, AND PROCESS	*1,675*	*86*
Fuel cells	1,295	
Class 320: ELECTRICITY: BATTERY OR CAPACITOR CHARGING OR DISCHARGING	*667*	*78*
Electrolyte	591	28
Class 204: CHEMISTRY: ELECTRICAL AND WAVE ENERGY	*568*	*214*
Anode	322	16
Cathode	320	34
Electrochemistry	192	18

There are at least two potential errors linked to this search procedure. One error might be that not only battery-related patents but also several other patents are extracted. This type of error was eliminated or at least substantially reduced through a manual scrutiny of all ‘battery-related’ patents for each automaker. Another error might be that too few or wrong patents are extracted. This was investigated using the following procedure.

1. A random sample from the large ~100,000 volume of 'automotive' patent records was created using a search criterion extracting patent records for a week in February each fifth year starting 1978 until 2008. This resulted in 590 patent records.
2. This sample was scrutinised manually using the full information for each patent. The result was that 14 patents were battery-related.
3. The same sample was then used for an automatic extraction of 'battery-related' patents using the search criterion described above. A total of 32 patent records matched the search criterion.
4. A comparison of the results from step 2) and 3) was finally made. It showed that (a) the automatic search procedure resulted in approximately twice the number of patent records, and (b) that among these 32 patent records, 13 out of 14 of the battery-related patent records identified in the manual procedure (step 2) were covered. Consequently, the quality check indicates that the search procedure will probably result in a number of battery-related patents close to but slightly lower than the actual number.

In this study, battery-related automotive patents were defined as patents relating to batteries for tractionary purposes in electric or hybrid electric vehicles. To qualify as battery-related, the patent must deal with the battery technology in some sense. Patents relating to electric or hybrid electric vehicles were only considered battery-related when they explicitly indicate a relation to the battery. Battery patents explicitly addressing the 12/14 V non-tractionary system were not included.

In the automotive context, the distinction between the architectural and component dimensions is possible to apply on several levels. Considering a hybrid electric vehicle (HEV) at a superior level, the powertrain can be considered a component in the complete vehicle. In the next level, the powertrain consists of a number of components such as engine, electric machine(s), power electronics and battery system. The battery system can in turn be divided into a battery management system and a battery pack, which in turn consists of cells mounted into modules. Even further, each cell consists of anode, cathode, separators and electrolyte. In Table 2, this is summarised.

Table 2: Product hierarchy relating to batteries in (hybrid) electric vehicles

Level	System	Components/knowledge (examples)
1	Powertrain	(Engine), electric machine(s), battery system, powertrain control
2	Battery system	Battery pack, battery management system (BMS), heating/cooling
3	Battery pack	Case, modules, heating/cooling, connectors, assembly

4	Battery modules	Case, cells, connectors, assembly
5	Battery cells	Anode, cathode, electrolyte, production

Based on this structure, a manual scrutiny of each ‘battery-related’ patent record was made, classifying the patent records in the groups ‘Not battery-related’ and the levels mentioned in Table 2.

Ideally, the involvement of battery makers in different types of tractionary applications should be studied following the same methodology. Unfortunately this was not possible as batteries obviously are a main business for battery makers and the borderline between knowledge with or without relevance for automotive applications is very hard to define. Furthermore, the various levels from cell to battery system are similar for many applications, not only the automotive ones. In order to at least get an idea of how the battery makers have approached the tractionary domain, the following methodology was used.

1. Two large battery makers were selected, one Japanese with close relations to Toyota (Panasonic), which has supplied all six automakers with batteries, and one with relations to all three US automakers (Johnson Controls-Saft, JCS). In the Panasonic group, patents assigned to Matsushita, Panasonic and Panasonic EV Energy (PEVE), and in the JCS group patents assigned to Johnson Controls, Saft, Varta and Delphi, were searched for. The total number of patents assigned to each group for the period of study was 33,579/5,088 for Panasonic and JCS respectively.
2. In both groups, a simple search criterion for battery-related patents with the keyword ‘battery’ was used as both firms have substantial business outside the battery development and production. This resulted in a sample of 1,070/332 ‘battery-related’ patent records for Panasonic respectively JCS.
3. To get a rough indication of how the battery makers have moved in the component and architectural knowledge dimension, it was assumed that patent records explicitly having a relation to an automotive context reflect an inclination in the architectural direction. The share of ‘automotive’ patents in the result from step 2 was extracted using a search criterion with the classes 180 and 903 and the keyword ‘vehicle’. The result was 282/134 ‘automotive battery-related’ patent records.
4. A quality check was carried out using a manual scrutiny of a random sample from all patents assigned to the two battery makers based on the patents issued during two weeks in February the years 1978, 1983, 1988, 1993, 1998, 2003 and 2008 with the result that out of a total of 412 patents, 12 patents were found battery-related.

5. A use of the search criterion for battery-related patents on the same sample resulted in 11 patent records.
6. In a comparison of the results from step 4) and 5), ten patent records matched and consequently two patent records were missed by the simple search criterion. In comparison to the methodology used for the automakers, this approach was less informative and therefore the results have to be used with more caution.

A potential problem in patent analyses is that, over time, firms change their names and structure. Consequently several different firm names might need to be added to obtain the total number of patents for a group such as Chrysler (Griliches, 1990). This was addressed in two ways. First, the firm's composition was investigated in terms of mergers and acquisitions up until the end of 2008. For the battery makers, which have been active in a rapidly changing business, this resulted in several additional firm names for each group. Secondly, only parts of the firm's name were used when searching for patents, as the full name potentially excludes a large number of patents assigned to the group.

Pilkington and Dyerson (2006) used patents to discuss the development of battery electric vehicles. They use only one patent class, comprising 268 patents for the whole period from 1976. This may be methodologically questionable and clearly makes the argument for an approach such as the one above, with its basis of more than one or just a few patent classes. In a study of another technological change in the automotive industry, Lee and Veloso (2008) used two parallel approaches, keywords and patent classes, to sort out patents. In addition to this, they manually checked each patent to verify its relevance and categorise it.

4 Development of batteries for traction

Among the main technological solutions being discussed for the vehicle of the future, all benefit from a hybrid powertrain and thus from an electrochemical energy storage system, such as a battery. Vehicles using internal combustion engines with conventional or alternative fuels are hybridised to increase their energy efficiency and reduce emissions (HEVs). In the case of plug-in HEVs, use of an alternative fuel (electricity) is also possible. Fuel cell vehicles (FCVs) are hybridised in order to increase the energy efficiency of the powertrain and improve the life expectancy of the fuel cells. Even 'pure' battery electric vehicles (BEVs) might be hybridised using two different energy storage systems in order to handle both energy and power storage efficiently. Consequently, even though there still is great uncertainty regarding the powertrain of the future, hybridisation and thus batteries is very likely to be part of the development. In this paper, (H)EV is used to denote all types of electric propulsion, from micro hybrids, via full hybrids to all-electric vehicles.

The market development so far has been cyclical with increased efforts to develop BEVs when shortages of oil were acute, for example during wars and the oil crises in the 1970s. In 1990, a mandate was adopted in California requiring car makers to sell a certain percentage of zero-emission vehicles beginning in the 1998 model year (Fogelberg, 2000). This stimulated car makers to do their utmost to develop zero-emission vehicles. Most of the large automotive firms began limited production and sales or leasing of BEVs in 1996 or 1997 (Kawahara, 1997). In December 1997, Toyota started deliveries of the Prius HEV in the Japanese market, and two years later Honda introduced their first Insight HEV on several markets. Nissan sold a small number of Tino HEVs in 2000. Ford introduced their first HEV powertrain in an Escape in 2004 and General Motors followed with a series of HEV introductions starting 2006. Until the end of 2008, the Japanese automakers and especially Toyota dominated the deliveries of HEVs, with approximately 95 respectively 80 percent for Toyota of the total volume (Honda, 2009; Hybrid Market Dashboard 2007; 2008; 2009; Kalhammer et al, 2007; Toyota, 2009).

A rough estimation of the total uncertainty as regards (H)EVs and tractionary batteries is that the uncertainty has decreased over time. A slightly more detailed estimate indicates that in the beginning of the 1990s, the ZEV mandate probably contributed to lower the demand uncertainty. Towards the end of the decade, the ZEV mandate lost most of its power and Japanese HEVs were introduced on the market. Since then, HEV sales have steadily increased and the technological feasibility has been confirmed. Consequently, it can be argued that the total uncertainty relating to (H)EVs increased from 1990 until around 1998 and thereafter decreased again. However, it has to be mentioned that there has been and is a continuous competition between various electrification alternatives from mild HEVs via full HEVs to plug-in HEVs, BEVs and FCVs.

Among the new technologies needed, batteries and fuel cells differ the most when compared to traditional automotive engineering, as they require the addition of electrochemical engineering skills to the traditional mechanical and electrical engineering ones.

4.1 Collaborative patterns in tractionary battery development

As is common in industries in relatively rapid technological change, the number of mergers, acquisitions and partnerships has been large in the firms working with batteries for propulsion. In Appendix 1, an attempt is made to describe battery firms with relations to the six automakers in this study. Figure 1 presents an overview of some of the six automakers' previous relations with battery makers and current ones for 2008, plus some of the vehicles in which the batteries are (scheduled to be) installed.

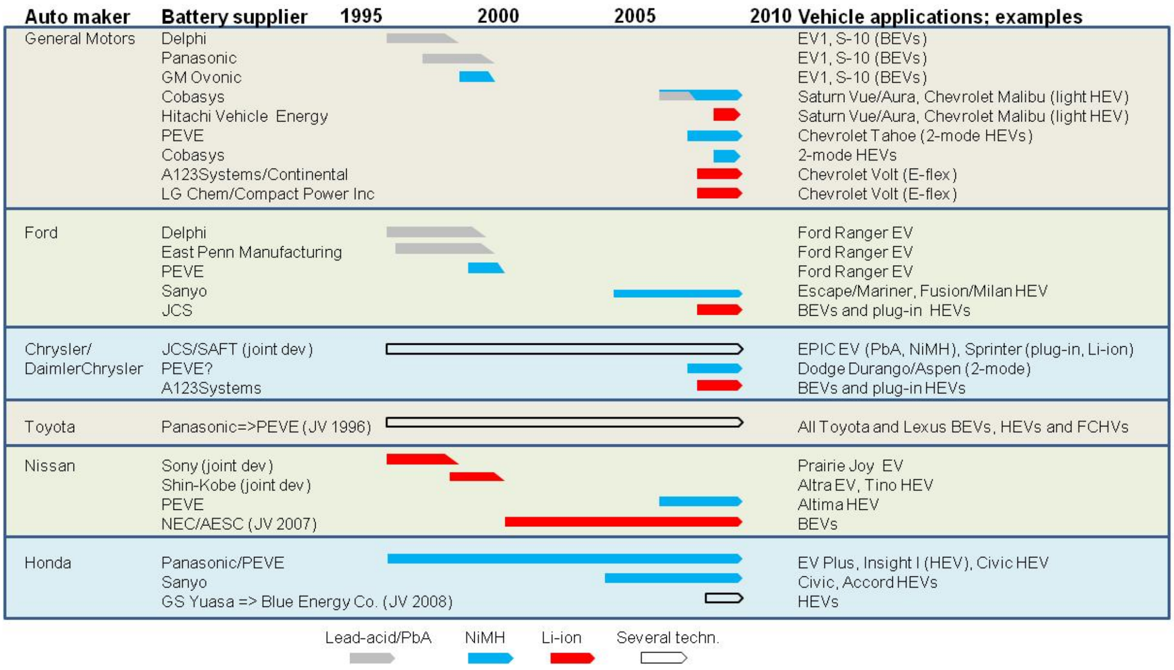

Figure 1: Automaker and battery maker relations

Some automakers use suppliers to make their battery systems, such as Continental and Cobasys using cells from A123 Systems for among others General Motors. Other examples include Magna Steyr supplying battery systems to Volvo based on cells from A123 Systems and the joint venture between Samsung SDI and Bosch named SB LiMotive supplying battery systems for BMW.

4.2 Study of patenting relating to tractionary batteries

In Table 3, an overview of patent data for the automakers is given. The number of patents granted for each automaker is in the same order of magnitude with a variation between 6,000 and 14,300. In the case of Honda, the manual scrutiny revealed a large number patents relating to another method to store electric energy; super capacitors. However, even though those are used in similar applications, they were not classified as battery-related in this study.

Table 3: Description of patent data for automakers

Patent type	Automaker						Comments
	GM	Toyota	Ford	Honda	Chrysler	Nissan	Chrysler includes DaimlerChrysler
All 1976 – 2009	10,714	12,199	10,211	14,310	6,072	9,764	
'Battery-related', whereof:	513	768	440	668	143	501	Search by patent classes and keywords
Battery-related total, whereof:	234	335	175	245	65	173	Manual scrutiny of each 'battery-related' patent record
Powertrain or above	44	97	70	111	28	60	Manual classification
Battery system	75	105	47	90	27	52	
Battery pack	26	28	12	17	9	13	
Battery module	21	36	4	15	0	17	
Cell	68	69	42	12	1	31	

In addressing the role of batteries in the powertrain of future vehicles, the development of the share of battery-related patents among the automakers was studied, see Figure 2. The data indicates that the share of battery-related patents has increased and the sharp rise around 1990 coincides with the launch of the Californian Zero Emission Vehicle Mandate.

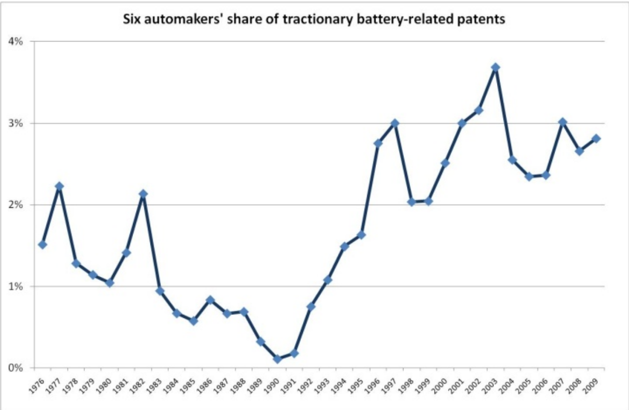

Figure 2: Battery-related patents in relation to all patents

However, each automaker has approached the battery technology differently. Figure 3, indicates the early dominance of General Motors and Ford in battery-related patenting, as well as the Japanese automakers' drastic increase in battery-related patent accumulation starting at the beginning of the 1990s. In comparison to Figure 2, Figure 3 presents the absolute numbers of patents, thereby introducing a risk that different patenting strategies may influence the figures, such as filing a lot of 'small' inventions versus only filing 'major' ones.

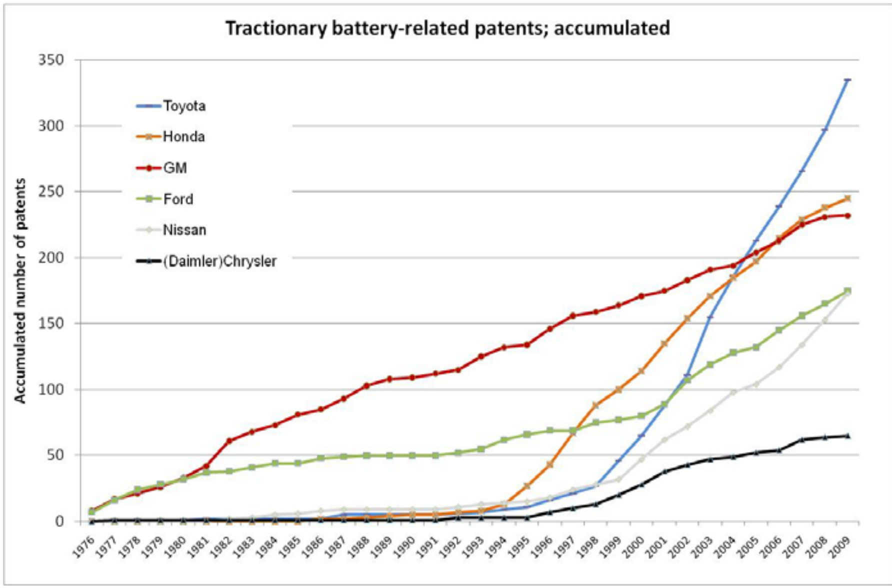

Figure 3: Accumulated number of battery-related patents

In Figure 4 - Figure 10, a visualisation of the automakers' focus in the architectural – component dimension is provided. Here, cell and module patents are counted as component patents, pack patents are equally distributed on the component and architectural side, and battery system and powertrain patents are counted as architectural. When comparing the figures, it is important to note that different scales are used for the vertical axis.

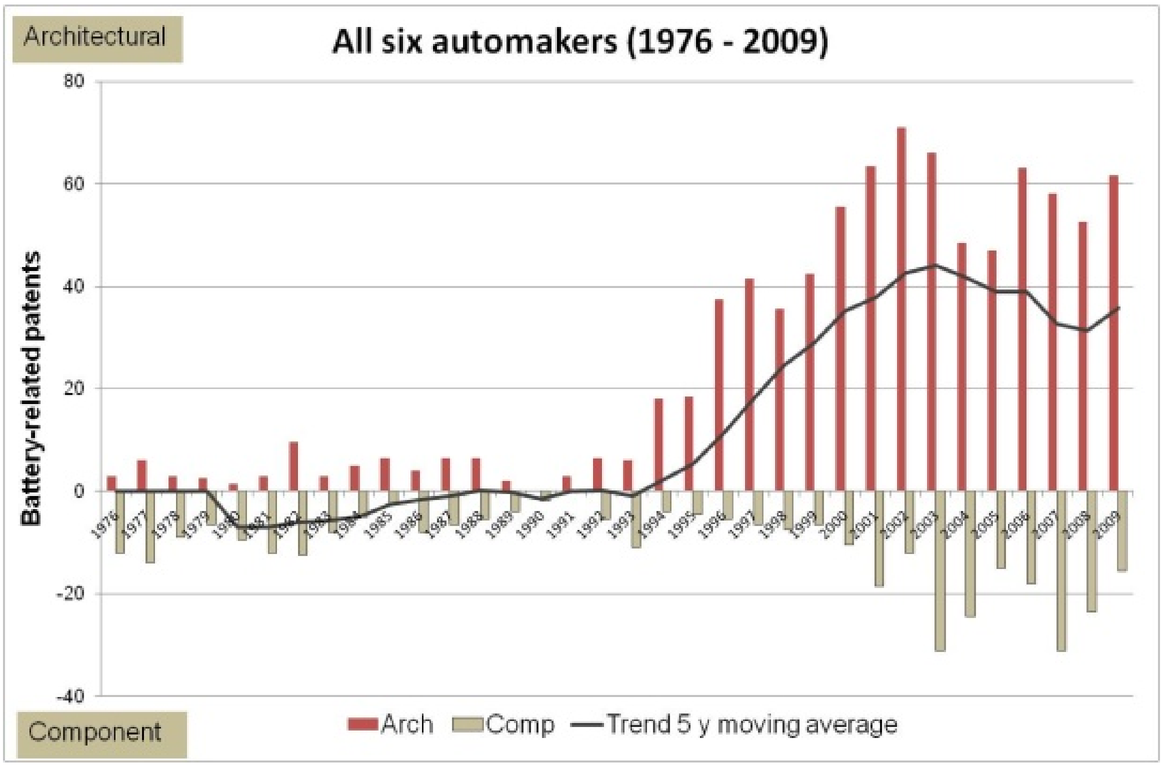

Figure 4: All six automakers

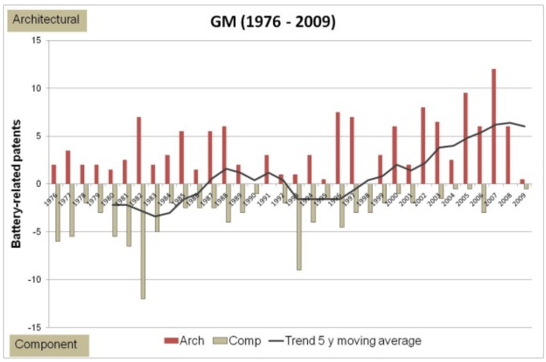

Figure 5: General Motors

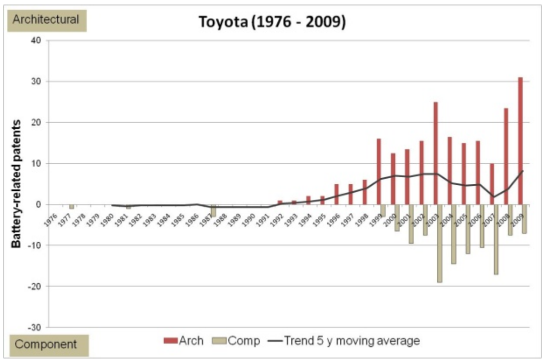

Figure 6: Toyota

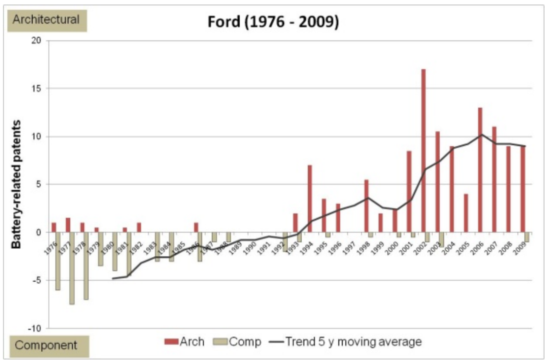

Figure 7: Ford

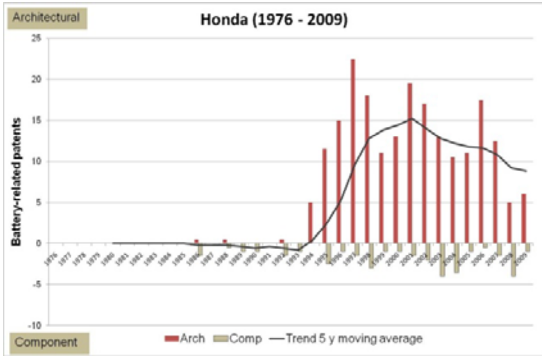

Figure 8: Honda

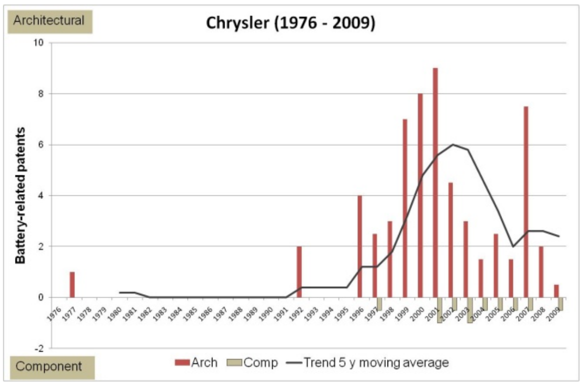

Figure 9: Chrysler

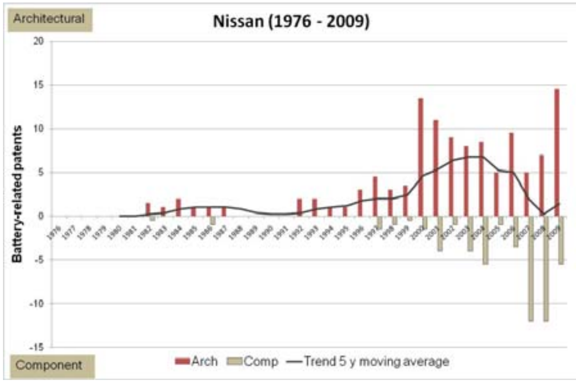

Figure 10: Nissan

On the aggregated level (Figure 4), data indicates a focus on the architectural side during the latter and most active half of the period of study. The largest absolute dominance of architectural patents was around 2002. When studying each automaker separately, large differences in strategy and focus are indicated. General Motors and Ford started early with a clear component focus and have thereafter moved towards an increased focus on the architectural side. The Japanese automakers started battery-patenting a lot later with an initial heavy focus on the architectural side. Since 2003, Nissan and thereafter Toyota appear to have the highest level of activity on the component side.

To obtain another perspective on the data for each automaker, the number of architectural patents was compared to the total number of battery-related patents. Here, a linear model was used giving cell patents zero, module patents 25%, pack patents 50%, system patents 75% and powertrain or above 100% in weight. Consequently, a number close to one indicates a strong focus on the architectural side and vice versa. In Figure 11 and Figure 12, this relative value is given for the six automakers together and separately with a polynomial trend of the second order. Figure 12 only covers the latter half of the period, when all six automakers were actively addressing tractionary batteries.

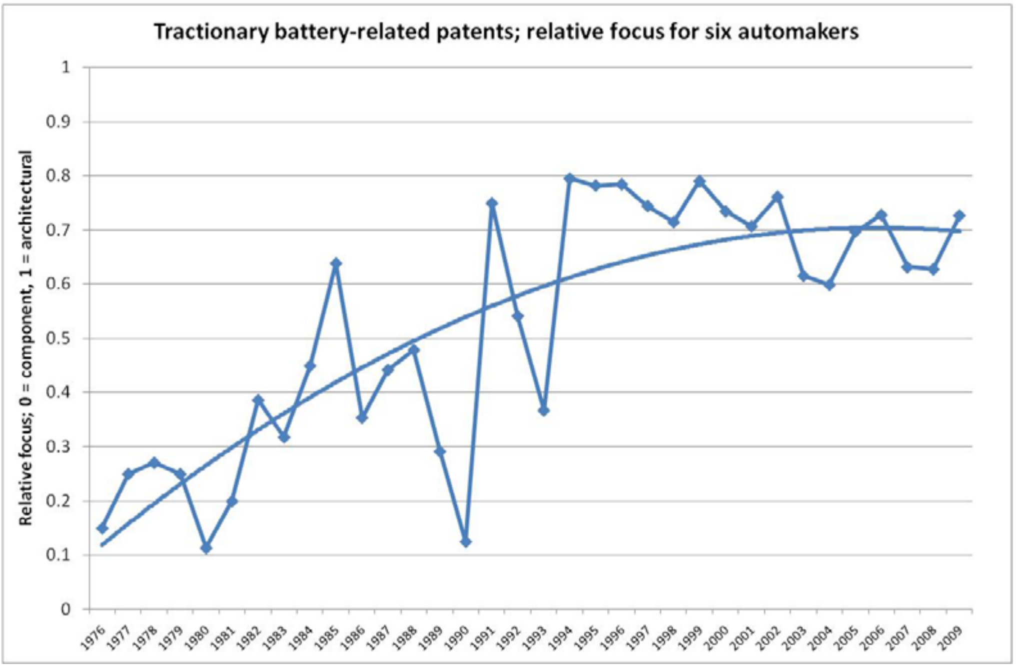

Figure 11: Six automakers' relative focus

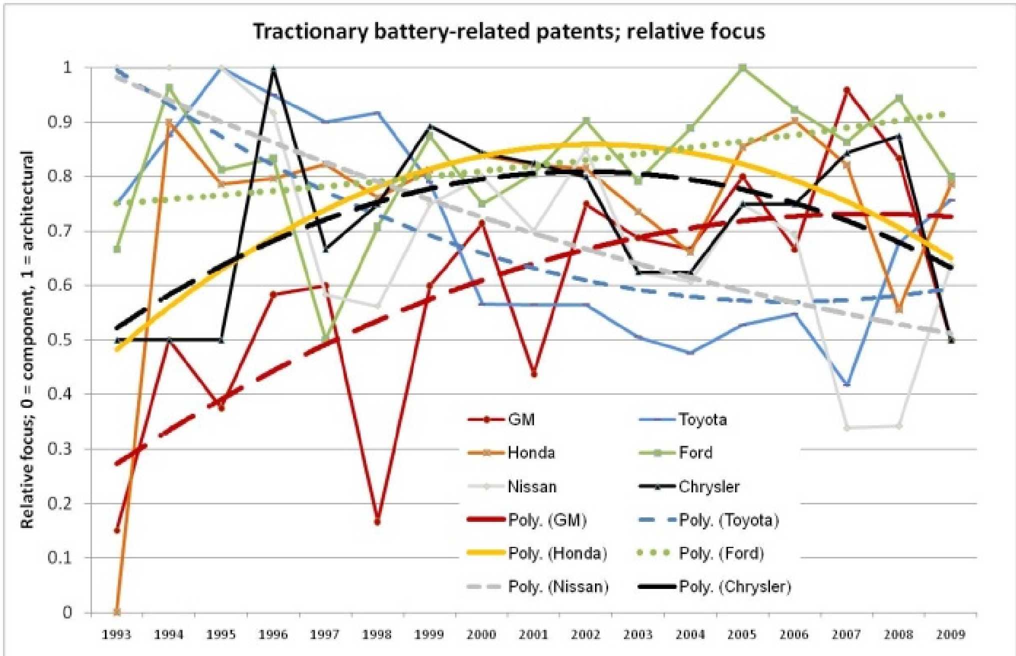

Figure 12: Each automaker's relative focus

The development of the relative focus over the period 1993 – 2009 indicates different trends with a general trend towards more architectural focus. Further, Ford appears very focused on the architectural side, whereas Nissan and Toyota move towards an almost neutral (0.5) focus.

Table 4: Description of patent data for battery makers

Patent type	Panasonic	JCS	Comments
All 1976 – 2009	33,579	5,088	'Panasonic' includes patents assigned to Panasonic, Panasonic EV Energy and Matsushita. 'JCS' includes patents assigned to Johnson Controls, SAFT, Varta and Delphi
'Battery-related', whereof:	1,070	332	Compare methodology section
Architectural	282	134	
Component	788	198	

As outlined in the methodology section, the battery makers were studied following a slightly different approach. In Table 4, basic data is given. It indicates that battery activities are a relatively smaller part of the activities in the large Panasonic group and that JCS has a larger focus on tractionary batteries. In Figure 13 – Figure 15, the development in each dimension is described for the period of study.

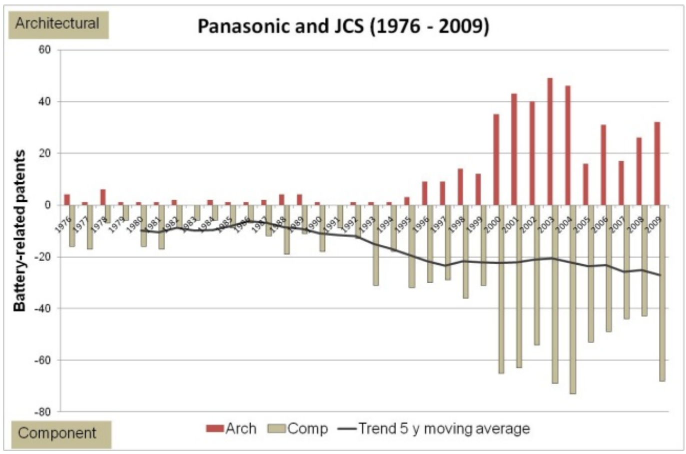

Figure 13: Panasonic and JCS

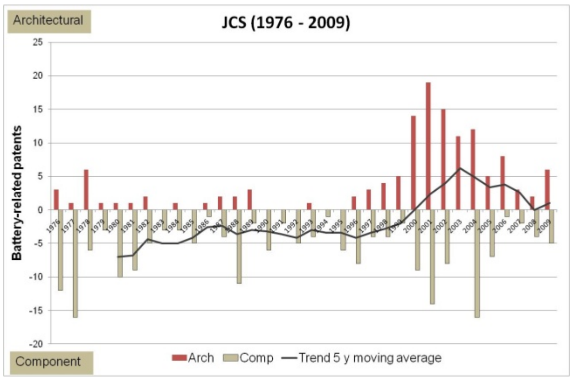

Figure 14: JCS

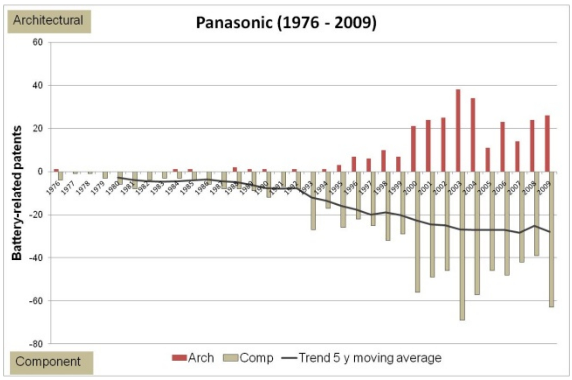

Figure 15: Panasonic

Figure 13 shows an overall trend towards more component patents. This is due to the large number of component patents assigned to Panasonic, whereas JCS has moved in the other direction towards more architectural patents. In comparison, Panasonic started architectural patenting very late but the group has anyway managed to file approximately twice the number of such patents than JCS. Finally, the relative focus for 1993 – 2009 is indicated in Figure 16. For both battery makers, it appears as if there has been a peak in architectural focus around 2004.

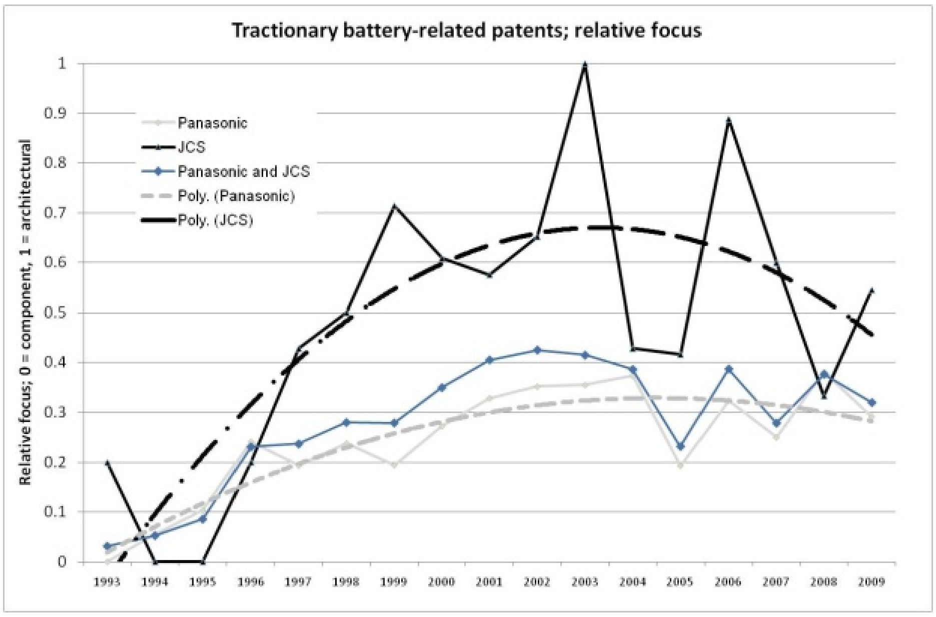

Figure 16: Relative focus for Panasonic and JCS

5 Discussion: inter-firm knowledge development in a potential paradigmatic shift in technolgy

First of all, empirical data indicates that the tractionary battery has become a key component for automakers. This is supported by the increasing number of relations being established between auto and battery makers, by the increasing share of battery-related patents granted, and by the general logic of electrification as a common denominator of the main known alternatives for future vehicle propulsion. All automakers have a large number of battery-related patents, which indicates an important role of in-house knowledge, as argued for in previous studies of knowledge partitioning (Lee and Veloso, 2008; Takeishi, 2001; 2002). However, no firm has opted for a full in-house development of the battery technologies.

Considering all six automakers, there would appear to be a US and a Japanese approach to knowledge base development (cf. Nonaka and Takeuchi, 1995). All three Japanese automakers have established strong ties to battery partners in the form of joint ventures (cf. MacDuffie, 2008). The US automakers have weaker ties, consisting mainly of supply agreements. This difference might be due to different traditions of working with suppliers but might also reflect the fact that the Japanese automakers introduced HEVs on the market 5 – 10 years earlier than the US ones. Consequently, they might be some years ahead in the HEV product life cycle.

In the terminology proposed by Henderson and Clark (1990), (H)EVs are a mix of architectural and radical innovations and probably closer to the latter. As argued by Wolter and Veloso (2008), this would imply a higher degree of vertical integration. This study does neither confirm nor contest this correlation. On another level, battery and even more the fuel cell technologies are typical examples where modularisation is expected to contribute to efficient production and lower costs. Empirical data confirms a vertical division of battery development and production. However, the automakers' development of fuel cells, which mainly takes place in-house, rather indicates a vertical integration.

A special case is the use of large suppliers such as Continental to manage relations to battery makers. Such an approach represents a focus on the higher level in the battery product architecture and an increased dependency on suppliers' knowledge, i.e. a clear case of knowledge partitioning (cf. Takeishi, 2001; 2002). It might be cost-efficient in the short run but potentially less so in the longer run, provided that batteries become core components in future vehicles. With an intermediate firm between battery maker and automaker, it appears more difficult to achieve the mutual exchange of knowledge that contributes to rapid learning.

Previous literature on automotive inter-firm relations and outsourcing mainly deals with relations between automakers and their existing suppliers, i.e. within the automotive industry. Even though this is the main case, it should be noted that also relations with firms predominantly outside the automotive industry are important; perhaps especially so in the early stages of potential paradigmatic shifts. This paper deals with one such example. Automakers need the expertise of battery makers (which is considerable as illustrated by the patent study) and battery makers must consider a new type of application for technologies which they have often been developing and manufacturing over a long period for a range of other applications.

In relation to the main objective of this paper, a further elaboration of previous literature is needed to facilitate the discussion. First, it is argued that high uncertainty motivates a high mutual overlap (Lee and Veloso, 2008; Takeishi, 2001; 2002; Zirpoli and Camuffo, 2009). As all component knowledge at the automaker can be interpreted as an overlap in relation to the suppliers (and vice versa), this implies that the overlap is bound to increase over time. One way to address this, in relation to the general uncertainty vs. overlap proposition seemingly conflicting perspective, is to introduce some kind of depreciation rate for the knowledge, see for example Hall et al (2009). Obviously some knowledge becomes outdated and, as noted by Olleros (1986), one factor contributing to the low success rates of first-movers is the threat of rapid obsolescence for early versions of products using radically new technologies. Another way is to use a relative measure instead of an absolute. In this case, the relative overlap would be the automaker's body of component knowledge in relation to the supplier's. If the supplier's body of component knowledge develops faster than the automaker's, the relative overlap decreases over time (and analogously for the overlap in architectural knowledge).

The relative overlap was calculated for the relation Toyota and Panasonic, which has been the most stable integrator – supplier relation as regards tractionary batteries. Figure 17 shows the accumulated number of patents in the component dimension for Toyota divided by the corresponding number for Panasonic, and a higher value corresponds to an increased overlap. Similarly, an increase in Figure 18, would also correspond to an increased overlap on the architectural side. The figures show that the relative overlap in knowledge appears to increase on the component side and remain stable on the architectural side (since the mid 1990s, when both firms started serious activities involving tractionary batteries).

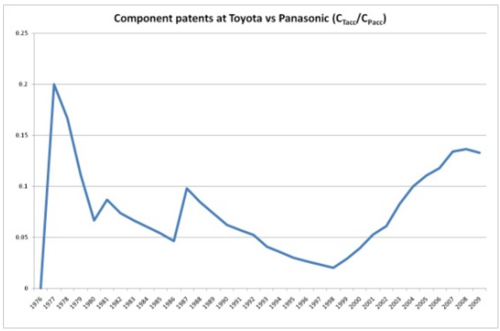

Figure 17: Relative overlap in component knowledge

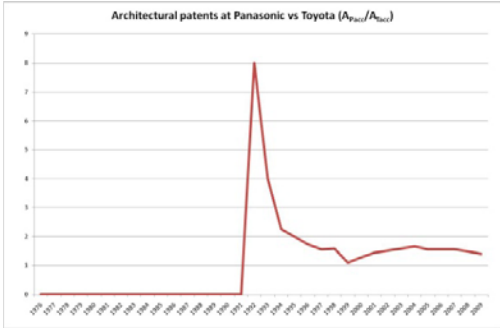

Figure 18: Relative overlap in architectural knowledge

Overlap may be a misleading term. Auto and battery makers may develop substantial bodies of component and architectural knowledge without duplicating each other. The crucial question might not be the relative 'overlap' but rather how the integrator and supplier(s) collaborate during different stages of the product life cycle. A close collaboration with one or a few suppliers would imply increased possibilities to share the tasks and knowledge in various ways, whereas looser relations would imply a higher need for in-house capabilities in order to maintain the independency. Empirical data indicates that when Toyota's battery patenting volume started to increase, it was with a focus on the architectural aspects, thus probably relying to a large extent on Panasonic's component knowledge. But in a broader perspective, the Japanese automakers closer relations to their battery makers would imply a reduced need for component knowledge. However, empirical data rather tells the opposite.

Table 5: Overview of empirical results relating to uncertainty

Period	Uncertainty	Overlap					
		Previous literature	Automakers		Battery makers		
			Absolute overlap (A-C)	Relative overlap (A/C)	Absolute overlap (C-A)	Relative overlap (C/A)
1976-2009	↘	↘	↘	↘	↘	↗
1990-1997	↗	↗	↘	↘	↘	↗
1998-2009	↘	↘	↘	→	→	→
A = architectural, C = component. The arrows indicate trends						

In Table 5, the uncertainty relating to (H)EVs for different periods is mapped against the trends in the auto and battery makers absolute and relative focus. The table indicates that the overlap-uncertainty relation proposed in the literature does not match the empirical data in four out of twelve positions.

The dominance of component innovation at the suppliers is in line with the traditional division of responsibilities between integrators and suppliers. As Panasonic became more involved in the development of tractionary batteries with Toyota, leading to a joint-venture in

1996, the number of architectural patents increased rapidly. Compared to Johnson-Controls-Saft (JCS), Panasonic had a stronger component focus, probably as Panasonic developed batteries for a wider range of applications. This can be valuable but also problematic. Battery makers with a long tradition outside the automotive industry might need a lot of encouragement and support to understand the conditions relating to automotive applications. Itazaki (1999) gives a detailed description of how Toyota and Panasonic jointly developed battery production to a completely new quality standard. Since the automotive industry is characterised by large volumes and low margins, it might also be difficult to find a battery maker willing to invest the substantial resources needed unless a clear outlet for its products is available.

The Lee and Veloso (2008) case study indicates that for automakers, there is an increase in component knowledge over the product life cycle, which dominates over the uncertainty effect. For the integrators, this is in conflict with the positive relation between uncertainty and overlap, as the uncertainty normally decreases over most of the product life cycle. Aggregated data for the automakers does not indicate a trend towards more component innovations in relation to the total number of battery-related patents. For the battery makers, the result differs between the absolute and relative trends.

Given the lack of coherence between the messages in previous literature and the empirical findings of this study, a search for additional factors potentially influencing the knowledge strategies of the firms was made. Below follows a discussion of some of them.

The timing of the market introduction of (H)EVs may be one factor influencing the relative focus on component and architectural knowledge. Toyota had almost only architectural patents until more than a year after its first HEV was introduced to the market. Similarly, the other automakers had a strong dominance of architectural patents in the period around their first market introduction of a HEV. It appears plausible that there is a focus on architectural matters in the later phases of a new vehicle development project before a market introduction. When new product development reaches a certain stage, the integrator as well as the supplier have to accept the state of the technology and focus on ‘making it work’, i.e. architectural knowledge. After the market introduction, there might be a renewed focus on component knowledge for the next generation of product.

The proposed link to the market introduction plans also illustrates a methodological issue. As the automakers have had different timing of their market introduction of HEVs, a study limited to aggregated data would have made it difficult to identify this type of potential rationale.

There is one (techno-)logical aspect which may explain some of the differences between automakers. A HEV of the power-split type (e.g. the Toyota Prius) uses a fairly complex powertrain where the battery is but one part of the total system. The control technology is one key issue to solve to make such a powertrain work. Activities and patents relating to this type of HEV may thus to a large extent relate to this system or architectural level. Another logic applies for battery-dominated plug-in hybrids or BEVs. In these vehicles, with a clearly less complex powertrain, the battery is a very central component and the success or failure of such vehicles (still to be confirmed in a mass market when this study was made) depends to a large extent on the lifetime, capacity and cost of the battery. One of the most aggressive promoters of BEVs is Nissan (and Renault), with very ambitious plans for commercialisation starting 2010. A focus on component patenting can also be noted in the Nissan data for the last period.

In the same vein, there may be a relation between the maturity of each battery technology and the relative focus on component and architectural knowledge. There have been a number of battery chemistries succeeding and overlapping each other, among them lead acid, nickel cadmium, nickel metal hydride and lithium-ion. In 2009, only nickel metal hydride batteries had reached mass production for tractionary automotive purposes, being the main technology in most HEVs. Large expectations were linked to lithium-ion batteries but in 2009, the techno-economical uncertainty related to this chemistry was still very high as regards tractionary applications.

As the study covers a long period, it should also be noted that general trends as regards outsourcing have changed over time. One example is that in the beginning of the 1990s, following the model of the Japanese automotive industry, other automakers started to develop closer relations with some of their suppliers. For various historical or tactical reasons, firm have different strategies, which may change over time. In 2009, General Motors declared that they prefer to work with several suppliers of batteries (or battery cells) and concentrate their own resources on the higher levels of the battery system. In contrast, Toyota pursued a strong in-house strategy for all new core technologies, thus even considering the joint-venture with Panasonic as an unwanted compromise. This difference in strategies is also reflected in the patent data.

Finally, one factor probably explaining some of the differences between the results of the study and the arguments in the literature is that the technology and its application are still very much developing and it may thus be too early to draw any conclusions. Further research in a later stage appears therefore of interest.

To summarise, this paper argues that potential paradigmatic shifts in technology imply genuine uncertainty and a need for new knowledge. Inter-firm relations is one way to increase knowledge, either through a limited number of close relations (e.g. the three Japanese automakers approach to tractionary batteries) or a multitude of more open relations (the US automakers). In relation to previous literature, this paper details the terminology used in relation to the component and architectural dimension, it investigates the uncertainty vs. overlap relation, and it proposes a number of additional factors potentially influencing the knowledge strategies. Furthermore, this paper indicates that a study of the component and architectural dimensions of knowledge gives several interesting perspectives on the strategies of the firms. This is in itself an argument for comparative studies, where different firms or groups of firms are studied separately, rather than aggregate studies, which miss such aspects. For the practitioner, the study highlights different firms' knowledge strategies but, due to the early stage in the potential shift to electric vehicles, it has to leave to the reader to consider which strategy is the best.

6 Conclusions

This study provides empirical support for the increasingly important role of batteries in a vehicle's powertrain, potentially leading to an elimination of the internal combustion engine. In this on-going potential paradigmatic shift, patent data indicates a rapidly growing firm-internal knowledge base. However, according to the mapping of six automakers collaborative efforts with battery makers, firm-external relations also appear crucial. Different approaches exist, basically implying a US and a Japanese style. In relation to previous literature, this paper details the terminology used in relation to the component and architectural dimensions, it provides partly conflicting messages as regards the relation between knowledge overlap, uncertainty and the product life cycle and it proposes additional factors potentially influencing the knowledge strategies. Finally, the variety in approaches to battery knowledge amassment provides a thrilling setting for a discussion of which is the winning strategy. But even though the Japanese actors in 2010 seem to lead in the HEV market, it is far too early to make any conclusions.

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Appendix 1: Suppliers of batteries for traction

A123Systems was established in 2001 to develop and manufacture Li-ion batteries. In collaboration with Continental, it has delivered some battery systems to General Motors for range extender plug-in HEVs, such as the Chevrolet Volt. However, the firm was not chosen to supply battery systems for the production model, the first deliveries of which are scheduled for 2010. In 2008, it was announced that Chrysler will use Li-ion batteries from A123 Systems for its production of BEVs and range extender plug-in HEVs starting 2010. A123 Systems also has a supply agreement with Delphi for Li-ion cells for mild HEVs made by SAIC Motor.

Cobasys was formed as a joint venture between Energy Conversion Devices (ECD) and Chevron in 2000. Between 1994-2000, one part of ECD, ECD Ovonics, ran a joint venture with General Motors; the GM Ovonic Battery. Cobasys has supplied General Motors with NiMH batteries for light HEVs in vehicles such as the Chevrolet Malibu and the Saturn Aura. In 2007, Cobasys entered into a partnership with A123Systems in which Cobasys will mainly provide the integration of A123Systems' battery packs.

GS Yuasa was formed in 2004 as a merger of GS (formerly Japan Storage Battery Co) and Yuasa. It owns the majority in a joint venture with Mitsubishi called Lithium Energy Japan established in 2007, as well as in a joint venture with Honda called Blue Energy Co, established in the end of 2008.

Hitachi Vehicle Energy (HVE) was established in 2004, as a joint venture between Shin-Kobe Electric Machinery, Hitachi and Hitachi Maxell. HVE has supplied Li-ion batteries for General Motors' Chevrolet Malibu and Saturn Vue/Aura HEVs. Shin-Kobe collaborated with Nissan in the later 1990s and supplied batteries for the Altra and Hypermini BEVs as well as the Tino HEV.

Johnson Controls-Saft Advanced Power Solutions (JCS) was formed in 2006 as a joint venture between Johnson Controls and Saft mainly targeting (H)EVs . Johnson Controls acquired Varta's automotive battery division in 2002 and Delphi's automotive battery business in 2005. At the end of 2008, JCS had supply or development agreements with such companies as BMW for mild HEVs; Continental for Mercedes S400 BlueHybrid; Ford for BEVs and plug-in HEVs; DaimlerChrysler for the Dodge Sprinter plug-in HEV; and General Motors for the Saturn Vue Green Line plug-in HEVs. Saft supplied batteries for most French BEVs from Renault and PSA in the 1990s.

NEC established the joint venture NEC Lamilion Energy in partnership with Fuji Heavy Industries in 2002. However, since 2006 NEC Lamilion Energy has been wholly owned by NEC. In 2006, NEC started to supply Subaru with batteries for BEVs. NEC and Nissan have had business relations since the 1990s and in 2007 they announced a joint venture entitled Automotive Energy Supply Corporation (AESC). This is expected to deliver Li-ion batteries for Nissan's (H)EVs and the Better Place project in which Renault-Nissan is also participating.

Panasonic (until 2008 Matsushita) established a joint venture with Toyota in 1996 called Panasonic EV Energy (PEVE), initially for the production of NiMH batteries. PEVE and Panasonic have supplied over one million NiMH battery packs to Toyota as well as Honda, General Motors, Ford and others. Panasonic's acquisition of Sanyo was announced in late 2008.

LG Chem has been awarded a couple of USABC development contracts (as will be explained later) through its US subsidiary Compact Power Inc (CPI) established in 2000. In 2007, CPI was awarded a battery system development contract by General Motors for its range extender plug-in HEV system and at the start of 2009, a supply contract for such vehicles with a commercial launch scheduled for 2010. In 2008, it was announced that LG Chem will be the supplier of Li-ion battery packs for Hyundai's Blue Drive HEVs.

Sanyo Electric Co has supplied NiMH batteries to Honda as well as Ford HEVs. In 2006, Sanyo signed an agreement with Volkswagen to co-develop NiMH batteries and in 2008 a new agreement was signed covering Li-ion batteries. Panasonic's acquisition of Sanyo was announced in late 2008.

Other battery makers having previous relations to the six automakers include Delphi (General Motors and Ford), Sony (Nissan) and East Penn Manufacturing (Ford).