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Inter-firm Relations Between Battery Suppliers and Electrical Vehicles Manufacturers: A Network Analysis

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Abstract: Global automotive industry is on the verge of a significant transformation into the transition to electrified transportation. This transition affects not only the automobile supply chain but also the battery manufacturing because batteries constitute an important part of electrical cars' production. Therefore, various manufacturers and countries are not only racing but also collaborating for battery manufacturing to be ahead of the technology race and hence improve their economic competitiveness and innovation capability. The aim of the study is to reveal the evolution of electrical vehicle battery manufacturing industry through the relationships between battery suppliers and electrical auto-makers by using the network analysis for 1997-2019 period. Another aim of the study is to investigate the role of these inter-firm relationships on determining the main actors of the electrical vehicle battery manufacturing industry. The study may have important implications to foresee the future of industrial actors belonging to battery manufacturing and automobile industry requiring both high level of innovation in the context of electrical vehicles.

Keywords: Network analysis, industrial economics, electrical vehicles, battery manufacturing, innovation economics.

Batarya Tedarikçileri ile Elektrikli Araç Üreticileri Arasındaki Şirketler Arası İlişkiler: Bir Ağ Analizi

Öz: Küresel otomotiv endüstrisinin, elektrikli ulaşım geçişte önemli bir dönüşümün eşiğinde olduğu gözlemlenmektedir. Bu geçiş sadece otomobil tedarik zincirini değil, aynı zamanda batarya üretimini de etkilemektedir, çünkü batarya elektrikli otomobillerin üretiminin önemli bir parçasını oluşturmaktadır. Bu nedenle, çeşitli üreticiler ve ülkeler bu konuda sadece yarışmakla kalmıyorlar, aynı zamanda batarya üretimi konusundaki teknoloji yarışının önünde olmak ve dolayısıyla ekonomik rekabetçiliklerini ve inovasyon kabiliyetlerini geliştirmek için işbirliği de yapıyorlar. Bu çalışmanın amacı, 1997-2019 dönemi için ağ analizi yoluyla, batarya tedarikçileri ile elektrikli otomobil üreticileri arasındaki ilişkileri inceleyerek elektrikli araç batarya imalat sanayinin gelişimini ortaya koymaktır. Çalışmanın bir diğer amacı da bu şirketler arası ilişkilerin, EV batarya üretim endüstrisinin ana aktörlerinin belirlenmesindeki rolünü incelemektir. Çalışma, elektrikli araçlar bağlamında yüksek düzeyde yenilik gerektiren batarya imalatına ve otomobil endüstrisine ait endüstriyel aktörlerin geleceğinin öngörülmesi açısından önem taşımaktadır.

Anahtar Kelimeler: Ağ analizi, sanayi ekonomisi, elektrikli araçlar, batarya üretimi, yenilik ekonomisi

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I. Introduction

The automobile manufacturing circuit contains complex set of relationships between vehicle assemblers and component suppliers, accounting for 50-70 percent of the cost price of an average automobile. As a result of time, price and technology or design driven pressures exerted by assemblers aiming to be competitive compared to their rivals, suppliers are facing consolidation and concentration conducted by mergers and acquisitions. In addition to all these pressures, there are also rising pressures to produce more efficient and cleaner cars meeting the requirements of environmental regulation related to emissions on the transition of transport to clean energy use (Dicken, 2015). Electric vehicles (EV) came up on these pressures that supported the demand for environmentally friendly vehicles and quickly started to build their own supply chain.

The demand for batteries, one of the main components of electrical devices and vehicles such as smartphones, electrical vehicles, trains, planes, is continuously growing every day. In today's technology, battery makers produce generally lithium-ion batteries to power them. By 2025, the lithium-ion batteries market is estimated to reach 94 billion dollars globally, due to the rising demand originated especially from the consumer electronics market (Zelenko, 2018).

In 2018, though global electrical vehicles sales grew 68% compared to previous year, these volumes are still too small compared to fuel powered cars: 1.26 million battery powered cars were sold in roughly 82 million passenger cars. EV sales are not at the same level with their fuel powered rivals, but it is estimated that EV sales will increase in accordance with country-level and city-level electro mobility targets due to global environmental issues. In parallel, most major automakers announce successively their intentions to produce electric powered vehicles in the near future. The expansion of global EV market is expected to be a key driver in increasing battery manufacturing capacity as well as in reducing battery unit prices (Global EV Outlook, 2019).

According to Bloomberg New Energy Finance, annual sales of electrical vehicles are predicted to rise from 1.1 million units in 2017, to 11 million in 2025, and to 30 million in 2030 (Bloomberg New Energy Finance, 2018). It is also estimated that EV batteries sales will rise from 450 million US dollar in 2015 to 35 billion US dollar by 2025, and 180 billion US dollar by 2040, and they will probably replace the current internal combustion engine-type automobile industry (Goldman Sachs, 2017). China is estimated to be the main market for EV batteries. According to strategists, by 2020, two out of three batteries will be produced in China which is also the main market for electrical cars (Berylls Strategy Advisors, 2018).

The economic studies regarding the electrical vehicles and battery production especially in the context of sustainability discourse appears to have increased in recent years. This interest may have risen because of several factors. Firstly, global automobile producers are integrated with the collaborative agreements with other manufacturers and technology joint ventures are notably important for these producers because of the huge production costs (Dicken, 2015: 490). The electrification of mobility and dynamic development of battery industry may therefore have strategic implications for industrial development due to large value chain of these industries that is being redefined and redesigned during the transition to clean energy. Secondly, since the electrical vehicles

market is a newly developing market, the technological collaborations in this market have not reached the maturity stage yet. Consequently, examining the evolution of inter-firm relationships between battery producers and EV makers may yield important insights into the future of battery and automotive manufacturing that are highly innovative industries.

Our aim in this study is to examine the evolution of inter-firm relationships among the battery producers and EV manufacturers through a network analysis and to reveal the importance of these relationships in determining the leading actors of EV battery industry. Thanks to the network analysis perspective, the most influential manufacturers, in other words the leaders, stand out based on their connectedness and their position in the global EV market. This analysis contributes to the literature as being one of the first study using the network analysis in the EV battery manufacturing industry for the period of 1999-2019. The evidence suggests that in the EV battery market, the dominance of the firms' collaborative efforts is mostly shaped by the profound sectoral innovations. While these efforts are predominantly on the national basis, multinational cooperation is also coming into prominence.

This study has been structured as follows: The first part is devoted to the historical evolution of EV battery production in the context of EV value chain. Next, the underlying literature review and research methodology is presented. Then, the findings from the research are indicated. Finally, some economic and policy implications are considered.

II. Development Of Ev Battery Manufacturing

Despite the highly competitive innovation race, the lithium-ion batteries used today are improved models of a technology developed almost forty years ago and commercialized by Sony in 1991. Since then, researchers in developed countries like South Korea, China, Japan and the United States and Europe tried to develop super battery that would allow electric vehicles to go for miles on a single charging as well as to improve EVs range (Zelenko, 2018). This range, considered to be the main issue on EV sales is determined by the energy amount stored in the batteries. Therefore, batteries are considered as the key differentiator among the EV producers (Horowitz and Coffin, 2018). It is assumed that the manufacturing of battery will represent up to 40 percent of the value creation of electrical cars. Accordingly, many large car producers aim to build their own battery factories to retain a bigger portion of value creation (Berylls Strategy Advisors, 2018).

A. Battery Suppliers and Automakers

According to battery technologies experts, the company who dominates battery market will also conquer the electrification of vehicles. China, Japan and South Korea dominate automotive battery production. Top global producers of batteries for electrical vehicles; Chinese CATL (Contemporary Amperex Technology Ltd) and BYD, Japanese Panasonic and South Korean LG Chemicals are racing to expand their battery

manufacturing capacity (Table 1). Panasonic and CATL are the world's leading EV battery manufacturers (Nikkei Asian Review, 2018).

Table 1: Battery Makers and the Automakers They Supply

Battery Makers	Automakers
Panasonic	Tesla, Toyota, Honda, Ford
CATL	BMW, Volkswagen, Daimler
LG Chem	Hyundai, Kia, Chrysler, Audi, Volvo, Jaguar, Ford, Renault, Daimler, General Motors
Samsung SDI	BMW, Fiat
SK Innovation	Daimler, Hyundai, Kia, BAIC

Source: Nikkei Asian Review, 2019.

Japanese automakers, early innovator of EV battery manufacturing, formed joint ventures to produce lithium-ion batteries with domestic electronics companies. Toyota partnered with Panasonic, while Nissan set up a joint venture with NEC or AESC. The aim of these venturing was to dominate the global EV market. However, the Japanese automakers faced tough competition first from South Korea and then Chinese rivals. Nissan Leaf launched in 2010 became the leader of global EV market. Nissan was forced to sell AESC to a Chinese renewable energy company as a result of price competition. China that was already the world's largest EV market, became the leader of EV batteries as well (Nikkei Asian Review, 2019). In 2018, The European commission launched the European Battery Alliance to develop a European battery ecosystem and so to get into the battery race. The USA supported the development of battery and EV drive systems through the collaborations with national laboratories and related industries (Global EV Outlook, 2019).

Japanese automakers are investing heavily in this race to get ahead again. For example, Toyota is heavily investing on research and development programs for next generation batteries such as solid state battery technology. Under the leadership of Toyota, 23 Japanese manufacturers started the all Japan development project to collaborate in new technologies including solid state battery. Solid state batteries seem to be the future technology of EV batteries due to many advantages including higher power capacity and energy density as well as better stability and security they offer compared to today's lithium-ion batteries. Panasonic built the Gigafactory lithium-ion battery factory of 5 billion US dollar worth with Tesla in Nevada. Though Panasonic is

the main battery supplier of Tesla, the world's biggest EV manufacturer, has lost market share to CATL. In April 2019, Panasonic aiming to reduce its dependence on Tesla decided to halt investment in EV battery plant run with the automaker. Like Panasonic, South Korea's battery producers have lost shares to Chinese makers. LG Chem is building new factory in China to be able to produce 500,000 batteries a year to supply electric-vehicle makers in China and other Asian markets by the end of 2019. Samsung SDI, supplying EV batteries for the BMW i3, BMW i8 and Fiat 500e has little presence in the Chinese market but it is foreseen that the company's sales in EV batteries will continue to grow thanks to rising demand from European carmakers (Nikkei Asian Review, 2019).

The United States, another important actor of EV manufacturing was an importer of lithium-ion batteries cells, but U.S battery manufacturing will tend to rise as Tesla's Gigafactory increases its production. Although Japan and South Korea are actually major lithium-ion cell manufacturers, 84 % of cell manufacturing is estimated to be in the United States or China by 2020 according to capacity expansions planned in these countries (Horowitz and Coffin, 2018).

New energy vehicles are an important strategic industry for China, the largest market of EVs. CATL, founded in 2011 as a spinoff of TDK's cellphone battery unit (supplier of Apple and other makers of mobile devices) became the world's top EV battery maker. It is building a new factory in China and plans to build its first overseas plant in Germany. Even though it left the leadership to CATL, China's leading battery company has been the BYD for many years. BYD, founded in 1995 is one of the companies powered by the Chinese state investing immensely in electrical vehicles to dominate the automotive industry in the future. The new 1.5 billion US dollar factory of BYD is considered to be BYD's core plant of its battery operations because the region is home to the largest saltwater lake accounting for 80% of the China's lithium reserves. The company aims to access to a stable supply of the main raw material to produce batteries and reduce its transportation costs (Nikkei Asian Review, 2019).

B. Electrical Vehicles Value Chain

EV batteries supply chain is generally consisted of cell manufacturing, module manufacturing and pack assembly stages that can be conducted in different locations. Figure 1 presents the simplified value chain of battery manufacturing. Raw materials including lithium and graphite are mined and then processed to be used to produce electrodes. Electrodes, main components of battery cells and cells are generally manufactured in the same facility. Materials and cell manufacturing can be located in regions with competitive advantages. Today, Asia, with its robust supply chain (from

materials to cell production) dominates EV cell production. In Japan, China and South Korea, existence of upstream materials suppliers provide supply chain clusters specialized on battery production and thus contribute to advantages of regional supply chain (Chung et al., 2015). However, battery pack in which cells and other components are assembled is typically located near the EV assembly due to transportation costs that are higher than cells or modules (Horowitz and Coffin, 2018).

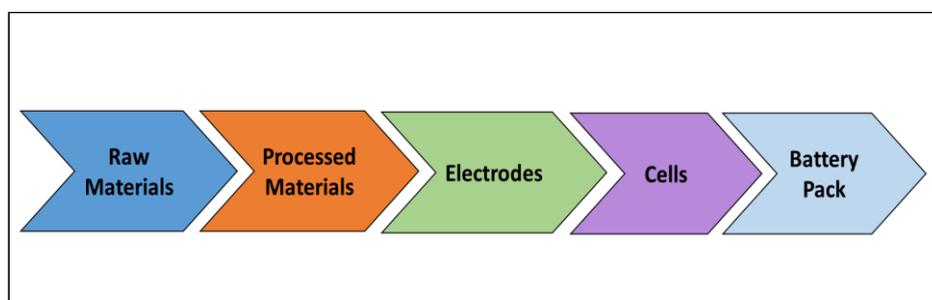


Figure 1: Automotive Battery Value Chain

Source: Chung et al., Simplified Automotive LIB Manufacturing Value Chain, 2015.

Automotive battery production competitiveness is affected not only from region-specific factors (labor, facilities and materials costs) but also from firm-level features. Compared to battery makers concentrated only in automotive markets, incumbent battery producing firms serving to consumer electronic markets benefits from several advantages due to their strong supply chain relationships and important manufacturing experience that they can transfer to automotive market (Chung et al., 2015). The development of battery industry value chain requires some policy supports reducing battery production investment risks such as the incentives for the establishment of charging stations, regulation for emission standards. Besides, effective allocation of research and development funds for battery technologies by governments is also another factor improving the battery industry value chain (Global EV Outlook, 2019).

III.Literature Review

Life-cycle of any commodity or business is gradually becoming short as a result of today's dynamic nature of innovation. In order to develop new products in a short time, firms prefer to collaborate through inter-firm network groups. These organizations exhibited especially in form of technological collaborations or financial alliances between automobile producers and their supply chain are studied by many researchers.

According to Abbott (2003), the standardization of automobile manufacturing system requires high level of collaboration with component suppliers that are under greater pressure than before to cover global quality standards and to globalize their manufacturing as well.

Monden (2018) proposed that the modularization of EV spare parts would be made via the closed or open networks between the auto-maker and the supplier. In initial or “closed” type modularization, there is an inter-firm network between the auto-maker, battery maker and electric producer to produce the battery for the industry. Japanese auto-makers including Mitsubishi, Honda, Nissan and Toyota investing in battery makers to form to some extent their “keiretsu” suppliers. Then in secondary stage, open modularization of the components will appear for the standard module to be used by lots of car makers, forming thus a “market network”. To give an example, LG Chem supplies batteries to Ford, GM, Hyundai and Renault (Monden, 2018: 91-93).

Another group of studies analyzed the transformation of automobile supply chain from the perspective of system integrator. As pointed out by Dicken (2015), the overall supply chain of the automobile industry is transforming. This transformation is mainly based on the prominence of tier 0.5 which connects the assemblers, automobile manufacturers to the rest of the supply chain, in other words, acts as system integrator.

The system integrator firm is the organization that sets up the network and leads it from an organizational and technological viewpoint. (Prencipe, 2005: 115). Moreover, Jarillo proposed the concept of hub firm, which sets up the network, and takes a proactive attitude in the care of it (1988: 32). Concretely, the system integrator firm coordinates, first, the development and production activities of a complex product, second, the knowledge bases relevant to those activities, and third, the relations among the participant firms and institutions. In this regard, the system integration capabilities can be categorized as synchronic (coordinating activities, knowledge bases and inter-firm relations within a given architecture) and diachronic (developing new capabilities and technologies in order to propose new architectures) (Prencipe, 2005). Thus, these capabilities cover the firm’s (system integrator) internal activities and knowledge bases as well as the activities and knowledge bases of a network of actors. As Hobday et al. (2005) indicate, system integration is not the counterpart to outsourcing, but the capability needed to manage outsourcing as well as ‘joint sourcing’ and ‘insourcing’. In the following part, our network analysis will highlight the system integrators transforming the battery manufacturing and thus whole EV supply chain.

IV. Research Method

The intertwined nature of relations in EV market and their evolution, especially between EV makers and battery makers, can best be explored and understood with the network analysis. Having its roots in sociology, the network analysis today is widely used in all disciplines of social sciences (Borgatti et al. 2009). The main idea behind the social network analysis is to analyze social or organizational entities within the webs of relations and interactions that they are embedded in. Each entity is defined as a node in these webs and the relations they develop within these webs are called edges. The network analysis allows us to distinguish and characterize the nodes based on the number of edges or relations they have, on how close they are to all other nodes in the network and on their role to connect the other nodes within the network. Various scholars have so far used the network analysis to examine the inter-firm relations in the context of

supply chain (Bellamy and Basole, 2013; Borgatti and Li, 2009; Choi and Hong, 2002; Kim et al. 2011; Lau et al. 2019; Madhavan et al. 1998; Provan et al. 2007) to highlight on the one hand the complexity of the relations within these networks and on the other hand the prominence of focal actors of these networks. In our study, the network analysis is used to examine the relations between EV makers and battery makers, to highlight the evolution in the EV battery market and to identify the most important battery makers that are or will become the focal actors in the EV market.

To implement the network analysis, a network with nodes and edges must be first built. In our study, while EV makers and battery makers are the nodes, the edges are defined as the supply and research agreements between those producers. It is however important to recognize and mark that the relations between EV makers and battery makers are not only limited to production activities. Those firms are also linked to each other with financial agreements, equity stakes and investment activities. But we are not including these relations into our analysis for the moment. The edge list, which shows which firm is linked to which firm, is created based on the supply and joint development agreements made by the EV makers. Using online search engine and EV makers' websites, we track down the agreements made by the EV makers and battery makers. Among different methods used for sampling, in this study the snowball sampling is used to determine the ties between manufacturers. As stated by Wasserman and Faust (1994), the snowball sampling, which is based on identifying the connections of a previously specified set of actors until no further connection is identified, is applied when the boundary of the network is unknown. In this study, the EV maker-battery maker network is constructed starting from EV makers. While the oldest agreement dates back to 1997 between Panasonic and Toyota, the cumulative number of agreements per year increases as the new actors enter the EV market throughout the years (Figure 2). Finally, a total of 131 agreements is identified for the period between 1997 and 2019. Considering the unbalanced distribution of those agreements throughout the years, the relations between EV makers and battery makers are analyzed in three overlapping periods; between 1997 and 2009; between 1997 and 2017 and finally 1997 and 2019. This choice of grouping the whole period into three overlapping periods can be justified by the aim of our study which is about identifying the focal actors, the potential system integrators of the EV market. If two firms start working in a joint development project or signs a supply agreement at a particular year, then the connection between those firms begins at that year and those firms can no longer be considered unrelated to each other. They can always use the connections made during their first engagement within their future projects even they don't continue to work together. That's why, an agreement made in a given year is taken as a start of a relation in our study and three networks are constructed using three overlapping periods (1997-2009; 1997-2017; and 1997-2019) accordingly.

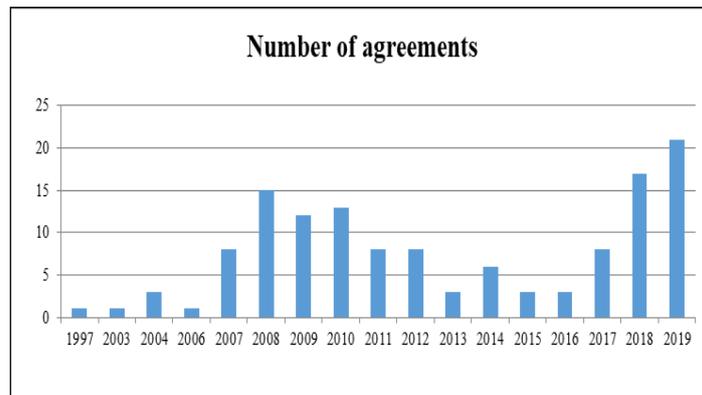


Figure 2: The number of agreements between 1997 and 2019

Source: Authors' calculation.

Based on the networks which are constructed using Ucinet (Borgatti et al. 2002), three centrality measures are computed: degree centrality, betweenness centrality and closeness centrality. All in all, centrality is related to the power and the control of a firm over other firms within the network (Bellamy and Basole, 2013), whereas each centrality measure is associated to relatively different aspects of power that a firm can exercise within these networks.

The degree centrality measures the number of links held by each node (Freeman, 1978). In the context of inter-firm relations, the number of ties maintained by a firm is related to the number of information and knowledge sources that it can directly reach. Thus the more ties a firm has, the greater amount of knowledge it can receive in the joint development projects (Ahuja, 2000).

The closeness centrality assigns a score to each node based on their shortest path to all other nodes. This centrality includes indirect ties of a firm, which let this firm access to a larger scale of information and knowledge base than it would obtain from its direct ties. Thus it is considered valuable source for exchange of resources within an inter-firm network (Ahuja, 2000; Provan et al. 2007). The closeness centrality is also related to the autonomy of a firm in the network (Freeman, 1978; Kim et al. 2011). A firm with a high closeness centrality is considered less reliant on other firms and thus less prone to risks, since it can reach the necessary resources from multiple indirect sources. Finally, Lau et al. (2019) find that the firm performance is positively related to the closeness centrality of a firm.

The betweenness centrality measures the number of times a given node stands on a path between two given nodes. Regarding the inter-firm relations, a high score indicates a strategic position for starting and controlling collaborations within the network (Freeman, 1978; Kim et al. 2011). This centrality measure is often associated to the concept of “structural holes” developed by Burt (1992). Structural holes are defined as gaps of information and knowledge flows between nodes which are connected to one specific node but not connected to each other. According to the structural holes theory, nodes which are located at the center of such holes have access to many distinct information flows, which maximizes their capacity to innovate (Burt, 1992). However, this position may also work against the firm to the extent that it increases the possibility of opportunistic actions and thus such firms may be distrust by other firms (Ahuja, 2000; Xiao and Tsui, 2007), which in return may negatively affect the firm performance (Lau et al. 2019).

V. Findings

A. Network between 1997 and 2009: The early period

As Figure 3 indicates, the network between 1997 and 2009 consists of 32 actors, 14 battery makers (shown with red circles in the figure) and 18 EV makers (shown with blue squares in the figure). The network and thus the EV industry in this period are mostly dominated by United States based manufacturers. The average degree centrality, which gives the average number of links of a given node, is computed as 2.786 by Ucinet. Analyzing the centrality measures (Table 2), among the battery makers those that have the highest degree centrality are **A123, Johnson Controls and EnerDel**, all United States based battery makers. In other words, these are the battery makers that have the highest number of direct relations within the network.

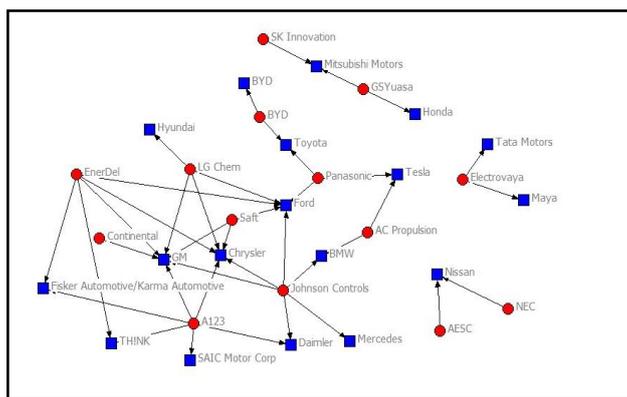


Figure 3: The network between 1997 and 2009

Table 2: Normalized Centrality Measures Between 1997 and 2009

Battery Makers	Degree Centrality	Closeness Centrality	Betweenness Centrality
A123	0,2	0,376	0,079
AC Propulsion	0,067	0,313	0,012
AESC	0,033	0,371	0
Electrovaya	0,067	0,375	0,002
EnerDel	0,167	0,406	0,066
GSYuasa	0,067	0,379	0,005
Johnson Controls	0,2	0,43	0,14
LG Chem	0,133	0,396	0,057
NEC	0,033	0,371	0
Panasonic	0,1	0,376	0,116
Saft	0,1	0,385	0,013
SK Innovation	0,033	0,37	0

Source: Authors' calculation.

Analyzing the closeness centrality measures, we find out that **Johnson Controls followed by Enerdel and LG Chem** is the battery maker having the highest score. In other words, they keep the shortest paths to other nodes within the network. Analyzing the degree centrality and closeness centrality measures together, Johnson Controls and Enerdel both enjoy information and knowledge flows from direct as well as indirect ties. Finally, regarding the betweenness centrality, **Johnson Controls** appears again as the battery maker having the highest score, which shows that this battery maker connects manufacturers which are not directly connected. Considering all of the centrality measures together, **Johnson Controls** is the most influential battery maker in the network between years 1997 and 2007. Thus this United States based battery maker appears as a potential system integrator for the EV industry for this early period.

Another battery maker displaying interesting figures in this early period is **Panasonic** having a low degree centrality but high betweenness centrality. When examined closely, Panasonic has only three connections; Toyota, Tesla and Ford, which are not directly

tied to each other. While this position may offer special advantages to Panasonic, such as starting collaborations between those manufacturers, Panasonic doesn't seem to capitalize this position so far. This manufacturer still continues its existing relations with those EV manufacturers separately and doesn't act proactively to start collaborations. As the network analyses of the following periods will show, while being one of the biggest battery manufacturers both financially and technologically, Panasonic chooses to keep its relations with its existing collaborators but doesn't create new ones, which hinders the potential for becoming a system integrator.

B. Network between 1997 and 2017

The network between 1997 and 2017 consists of 24 battery makers and 37 EV makers (Figure 4). The period between 2007 and 2017 is marked by the entry of Chinese manufacturers in the scene such as BYD, CATL, CALB, Guoxuan. The average degree centrality, which gives the average number of links of a given node, is computed as 3,125 by Ucinet, which shows that the network has become more and more connected throughout the years. Analyzing the degree centrality measures (see Table 3), the battery maker having the highest number of direct links by far is now **LG Chem** followed by **A123** and **Johnson Controls**. While the American A123 and Johnson Controls still keep relatively high number of ties within the network, the South Korean **LG Chem** multiplies its direct relations within the industry. Closeness centrality measures show that **LG Chem** is the closest battery maker to all other actors within the network, meaning that it has the shortest path to all nodes. Finally, **LG Chem** is again the battery maker having the highest betweenness centrality. Examining all of the three centrality measures together points us to LG Chem in the best position to control the collaborations within the network, thus as a potential system integrator.

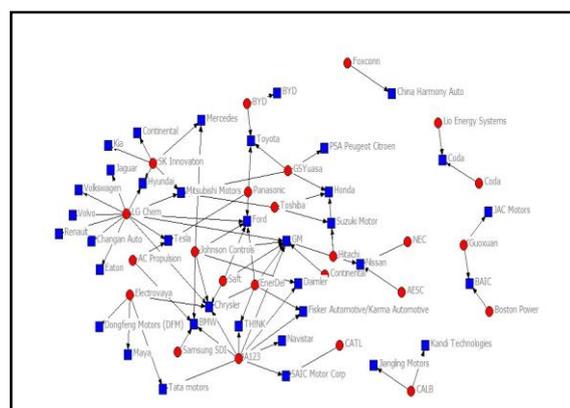


Figure 4: The network between 1997 and 2017

Table 3: Centrality measures between 1997 and 2017

Battery Makers	Degree Centrality	Closeness Centrality	Betweenness Centrality
A123	0,161	0,355	0,16
AC Propulsion	0,036	0,289	0,008
AESC	0,018	0,224	0
Boston Power	0,018	0,299	0
BYD	0,018	0,222	0
CALB	0,036	0,3	0,001
CATL	0,018	0,23	0
Coda	0,018	0,296	0
Electrovaya	0,071	0,295	0,061
EnerDel	0,089	0,338	0,037
Foxconn	0,018	0,296	0
GSYuasa	0,071	0,294	0,056
Guoxuan	0,036	0,302	0,001
Hitachi	0,071	0,338	0,123
Johnson Controls	0,107	0,355	0,073
LG Chem	0,286	0,395	0,263
Lio Energy Systems	0,018	0,296	0
NEC	0,018	0,224	0
Panasonic	0,054	0,292	0,038
Saft	0,054	0,33	0,009
Samsung SDI	0,018	0,248	0
SK Innovation	0,089	0,314	0,044
Toshiba	0,054	0,285	0,013

Source: Authors' calculation.

Table 4: Centrality measures between 1997 and 2019

Battery Makers	Degree Centrality	Closeness Centrality	Betweenness Centrality
A123	0,15	0,343	0,22
AC Propulsion	0,033	0,275	0,01
AESC	0,017	0,222	0
Boston Power	0,017	0,159	0
BYD	0,017	0,227	0
CALB	0,033	0,115	0,001
CATL	0,183	0,341	0,171
Electrovaya	0,067	0,269	0,077
EnerDel	0,083	0,305	0,03
GSYuasa	0,067	0,283	0,037
Guoxuan	0,05	0,225	0,093
Hitachi	0,067	0,303	0,044
Ionic Materials	0,05	0,264	0,01
Johnson Controls	0,1	0,323	0,046
Kandi Technologies	0,017	0,114	0
LG Chem	0,217	0,368	0,265
Maxwell	0,017	0,231	0
NEC	0,017	0,222	0
Northvolt	0,033	0,276	0,002
Panasonic	0,067	0,293	0,03
Saft	0,05	0,299	0,007
Samsung SDI	0,033	0,276	0,002

SK Innovation	0,1	0,294	0,063
Solid Power	0,033	0,275	0,002
Toshiba	0,067	0,283	0,017

Source: Authors' calculation.

VI. Conclusion and Discussions

The development of electrical cars has been one of the important innovation field being at the center of new value creation in automotive industry. As the batteries form the heart of electric cars, battery manufacturing is also undergoing significant transitions. These transitions include the innovation race for battery technologies as well as the important investments made to expand battery productions. In connection with this, the battery supply chain, key element of battery production, becomes increasingly fundamental.

In this study, the relations between leading EV makers and battery makers were examined to determine the most important actors in EV battery manufacturing. This work contributes to the literature on the relationship among the firms of automobile industry and battery manufacturing requiring both high level of innovation and technology, highlighting the role of strategic business collaboration. Our study has some economic and policy implications which will be discussed below.

The United States, China, Japan and South Korea appear to be the most important actors of EV battery supply chain. More specifically, China appear to be the world leader in value added for EV batteries due to its high level of sales of locally manufactured EVs that are mostly consisted of locally manufactured batteries and cells. Furthermore, according to our network analysis, in the early period of battery manufacturing (1997-2009), US based firms dominate the supply chain as well as the technological leadership. Then, if the relations among battery manufacturing and EV makers in 2010-2017 period are included to the study, the South Korean firm, LG Chem is found as the battery maker having the highest betweenness centrality, exhibiting the best position to control the collaborations within the network. Finally, when the 2018-2019 period is included, LG Chem remains as the battery maker having the highest centrality followed by the Chinese CATL and the US A123. These three battery makers have also the highest scores in terms of betweenness centrality measures. Since the battery manufacturing has a very dynamic structure and nature, updating this type of analysis may yield different findings in the future.

The electrical vehicles uptake and related battery manufacturing developments imply bigger interest for studies including inter-firm relations among battery producers and EV makers. In this context, understanding the structure of the battery supply chain and evaluating firm-level relationships affected from increased demand for EVs may have important implications for industrial organizations belonging to these two industries that will shape the future. Studies focusing on relations of these two industries with other industries to investigate their spill-over effects may provide different perspectives and may also give fruitful insights on how will the innovation race shape the future's business organizations as well as the importance of strategic leadership and management during this race.

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