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Shifting grounds: How industry emergence changes the effectiveness of knowledge creation strategies - The case of the U.S. automotive airbag industry

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Abstract

This paper investigates the effect industry life cycle phase shifts have on the effectiveness of firms' knowledge creation strategies. Building on literature streams on strategic knowledge management and industry life cycles, we develop theoretical arguments for why the best knowledge search strategy should be different before the emergence of an industry compared to afterwards. Testing our hypotheses empirically in the emerging U.S. automotive airbag industry confirms the powerful forces of industry emergence: the best knowledge search strategy is initially one that looks inward into the organization but outside of the technology area, and later shifts to one that is looking outward from the organization and the technology. As practical implication we derive that R&D managers should (i) adjust their teams' knowledge search strategies depending on the industry life cycle phase in which they find themselves, and (ii) especially look for new applications of their firm's existing knowledge in related fields.

Keywords: Knowledge Management; Search Processes; Industry life cycle; R&D; Patents, Corporate Entrepreneurship

Introduction

Knowledge is increasingly considered a critical valuable resource, particularly for companies developing high-technology products and systems. Recent research has placed an emphasis on the capability of knowledge creation as an important explanatory variable of firm performance (Argote, McEvily, & Reagans, 2003). Early research on organizational learning has established the cumulative nature of knowledge creation (Cohen & Levinthal, 1990). In other words, knowledge creation has been conceptualized as a repeated experience exercise along a path, a path that can either explore local knowledge neighborhoods or bridge more distant knowledge areas. More recent research has shown that this distance contains multiple dimensions, including both technological and organizational aspects (Ahuja & Lampert, 2001; Katila & Ahuja, 2002; Rosenkopf & Nerkar, 2001).

Most of the existing research has studied the phenomenon of knowledge creation in relatively mature industries. What is less known is whether the same knowledge building strategies are effective in emerging industries, i.e., in situations in which firms, knowledge, and industries co-evolve. This question is increasingly relevant given that technological change is accelerating and time frames of continuing industry leadership are shortening. For example, almost 50% of the companies on the 1999 Fortune 500 list were no longer on that list in 2009. This paper aims to contribute to filling this gap by exploring the effect of industry emergence on the most effective knowledge building strategy.

The remainder of the paper is organized as follows. In the next section we discuss the relevant literature and formulate our hypotheses. Section three presents an overview of our data and methods. The empirical results are presented in section four, section five provides the corresponding discussion of the findings including theoretical and practical implications, and section six concludes.

Theoretical background and hypotheses

Characteristics of knowledge creation as cumulative search process

If knowledge creation is interpreted as a cumulative process, i.e., newly created knowledge searches for, and builds on, existing knowledge, the question of path dependence of this process arises. Early research on knowledge creation has emphasized the importance of a firm's existing knowledge. Knowledge which is familiar to the firm yields more immediate and likely returns (Levinthal & March, 1981), and creates an 'absorptive capacity' enabling the firm to recognize the value of new and external information (Cohen & Levinthal, 1990).

However, building only on closely related knowledge has its limitations built-in. While this type of local search leads to the formation of 'core capabilities,' it also increases the risk for firms to develop 'core rigidities' (Leonard-Barton, 1992). This tension between the pros and cons of narrow but deep and shallow but wide searches for knowledge creation strategies has led researchers to suggest that over the long run organizations need to develop 'ambidexterity' (Tushman & Oreilly, 1996), 'combinative capabilities' (Kogut & Zander, 1992), or 'dynamic capabilities' (Teece, Pisano, & Shuen, 1997) to overcome these challenges.

More recently, research has begun to unpack what it means for knowledge to be closely related, i.e., what constitutes local vs. distant searches. Various dimensions along which to study knowledge relatedness have been suggested, e.g., knowledge characteristics such as proximity, commonality, and complementarity (Breschi, Lissoni, & Malerba, 2003), knowledge subjects such as product, customer, or management (Tanriverdi & Venkatraman, 2005), or knowledge sources such as customers, competitors, suppliers, and Universities (Laursen & Salter, 2006; Paananen, 2009).

On the technology level, Ahuja and Lampert (2001) consider both firm boundaries and industry boundaries to distinguish various levels of distance, i.e., technology newness, which they label novel, emerging, and pioneering technologies. On the firm level, Katila and Ahuja (2002) define search depth by the frequency with which a firm reuses old knowledge and search breadth by how widely a firm explores new knowledge territory. Finally, Rosenkopf and Nerkar (2001) combine both technological and organizational dimensions to define four types of knowledge exploration a firm can engage in, and their measure for distance assesses whether or not the search processes crosses a technological boundary, or an organizational boundary, or both.

Industry emergence

In a separate stream researchers have been searching for regularities with which industries evolve and change over time (Fine, 1998; Foster, 1986; Klepper, 1997; McGahan, 2004; Schumpeter, 1942). One widely used theory to explain how industries evolve has been the industry life cycle – or product life cycle, because particularly early on many industries are defined by a single product, e.g., typewriter, automobile, computer (Abernathy & Utterback, 1978; Utterback, 1994). Core idea of this theory is that industries go through a sequence of recognizable phases. It suggests that industries start from a fluid phase in which an increasing number of firms enters the industry and competes with a broad variety of solutions. In the subsequent transitional phase the market grows and firms' foci begin to shift from product to process innovation. Finally, in the specific phase the industry matures and competition is driven by cost considerations and the number of participating firms declines (Klepper, 1996; Klepper, 1997; Utterback, 1994).

The crucial consequence of industries evolving through phases is that for firms in those industries the competitive environment changes from one phase to another. Several aspects such as dominant designs, timing patterns of firm entry and exit, and sales take offs have been identified as playing key roles in shaping the competition in an emerging industry. Due to its standardizing effect, the dominant design – once it is established – makes competing very difficult for firms who previously bet on a contending design. For the disk-drive industry it has been empirically shown that firms who enter an industry immediately prior to the emergence of a dominant design increase their survival chances (Christensen, Suarez, & Utterback, 1998). Broad entry timing differences seem to be more relevant than smaller variances: Agarwal and Bayus (2004) find in their study across a broad range of innovations that what matters is the timing difference between cohorts, not within cohorts. The ultimate confirmation of a design's dominance occurs when it becomes accepted by the market participants (Rosa, Porac, Runser-Spanjol, & Saxon, 1999), i.e., with significant sales take-off. In most industries, there is a substantial incubation period of several years between product invention, market launch, and sales take-off (Agarwal & Bayus, 2002; Golder & Tellis, 1997; Kohli, Lehmann, & Pae, 1999).

Hypotheses

Following recent research that conceptualizes knowledge creation as search and recombination processes, we build on Rosenkopf and Nerkar's (2001) typology of four types of exploration to capture both technological and organizational boundary-spanning of these processes. Rosenkopf and Nerkar propose that knowledge search activities can cross organizational boundaries (external boundary spanning), technological boundaries (internal boundary spanning), neither boundary (local), or both boundaries simultaneously (radical) (Figure 1). However, in contrast to Rosenkopf and Nerkar, we do not investigate the knowledge search processes during an industry's mature phase, but rather during the period of the industry's emergence. For the purpose of this study we define industry emergence as the period when meaningful sales begin to materialize. Consequently, we formulate separate hypotheses for the industry pre-takeoff incubation stage and for the industry post-takeoff growth stage.

Insert Figure 1 about here

The theory on the industry life cycle suggests that technological discontinuities trigger the start of a fluid phase in which many firms enter an industry and compete for dominance with alternative products.[1] In such an industry pre-takeoff stage, neither a consolidated industry structure nor substantial industry-wide product knowledge exist yet, while alternative technologies compete for dominance (Abernathy & Utterback, 1978). In environments characterized by high levels of technological uncertainty, firms tend to prefer familiar knowledge over unfamiliar and can build specialized competencies by refining their internal knowledge (Levinthal & March, 1981; Nelson & Winter, 1982). In addition, to develop the capacity to understand and evaluate the potential of outside knowledge requires first the development of an own knowledge base (Cohen & Levinthal, 1990). Notice that the arguments above favor de alio firms who can build on knowledge that is internal to the firm but external to the new product technology over de novo firms. Thus, we formulate our first hypothesis as follows.

[1] Because we will define an industry by using technological knowledge categories, our use of the 'product technology' dimension becomes identical to what the industry life cycle theory (Utterback 1994) has labeled 'industry' or 'product,'

Hypothesis 1A: In the industry pre-takeoff stage, a firm exploring knowledge within its organizational boundary is more likely to develop high impact technological solutions than a firm exploring across its organizational boundary.

In addition to the organizational boundary we consider the product technology boundary as the second dimension of knowledge search processes. In the industry pre-takeoff stage where substantial industry-wide knowledge is limited by definition, a firm searching for new solutions only within the new industry limits itself. In contrast, prior to the existence of a dominant design firms compete with various technical solutions, originating from or inspired by other technologies. Thus, in case of an emerging industry it is not so much the knowledge exhaustion effect that can be observed when firms search only within the existing focal product technology space that leads firms to look elsewhere for superior solutions (Fleming, 2001), but rather the lack of a sizable knowledge stock in this new industry in the first place. In addition, searching a broader technology space in the industry pre-takeoff phase may also reduce the high risk of choosing a wrong technology in this early phase of the industry (Christensen et al., 1998).

Hypothesis 1B: In the industry pre-takeoff stage, a firm exploring within its organizational boundary but across the product technology boundary (internal boundary-spanning) is most likely to develop high impact technological solutions.

For the development of the next two hypotheses we shift our focus to the industry post-takeoff stage. In this industry stage, the technological path solidifies after the dominant design has been accepted in the industry and its associated market through experimentation and communication between suppliers and their customers (Rosa et al., 1999; Utterback, 1994). Firms who have set initially on another design either exit the industry (Anderson & Tushman, 1990; Suarez & Utterback, 1995) or adapt their technology to meet the technological path defined by the dominant design (Tegarden, Hatfield, & Echols, 1999). With an industry maturing, firms also become increasingly aware of their mutual dependence on knowledge and place more emphasis on being a part of larger technological communities (Gittelman & Kogut, 2003; Powell, Koput, & SmithDoerr, 1996). For these reasons, firms need to watch the technological developments of other firms in the industry. In addition, tapping into external knowledge can help reducing the risk of organizational rigidity (Leonard-Barton, 1992) in the industry growth phase.

Hypothesis 2A: In the industry post-takeoff stage, a firm exploring across its organizational boundary is more likely to develop high impact technological solutions than a firm exploring within its organizational boundary.

As for the pre-industry take-off phase, we now consider the product boundary simultaneously with the organizational boundary. The dominant design shapes a technological path in an emerging industry. Once such a path is created, a firm may be locked out of the market if a solution other than its own has become the dominant design and the firm is unable to develop products compatible with the accepted technology (Schilling, 1998). In this stage, firms are more likely to succeed by choosing and refining the accepted technological path rather than creating a new one as the industry evolves. Moreover, if knowledge is new not only to the industry but also to the firm it can cause information overload and assimilation problems (Ahuja & Lampert, 2001; Kogut & Zander, 1992).

Hypothesis 2B: In the industry post-takeoff stage, a firm exploring across its organizational boundary but within the product boundary (external boundary-spanning) is most likely to develop high impact technological solutions.

Data and Methods

Industry and Product

We choose as our setting the emerging U.S. automotive airbag industry because the airbag is a multi-technology device whose design and manufacture requires diverse technologies such as mechanical, electrical and electronic, computing, chemical, and textile technologies. In addition, the airbag industry grew from being almost non-existing to a multi-billion dollar industry in less than 15 years, and its emergence in the early 1990s lends itself to proper analysis without creating censored data problems. While some technical development activity on automotive airbags occurred in the 1960s, legal challenges between automotive industry and US governmental agencies delayed the large-scale market introduction of airbags by twenty years. Then, in the 1980s, a combination of a National Highway Traffic and Safety Administration (NHTSA) ruling requiring automobile manufacturers to introduce passive restraint systems in their vehicles, several Supreme Court rulings, changes in management in some of the car companies, and pressure from the Insurance industry resulted in all new passenger cars being equipped with first driver and subsequently passenger front airbags in the late 1980s and early 1990s (Figure 2).

A typical automotive airbag system consists of four main components: a sensor that senses a vehicle's deceleration rate, a diagnostic and control unit whose algorithms determine whether a crash has actually occurred, an inflator that in case of a crash rapidly inflates the bag, and the bag itself as the protective device.

Insert Figure 2 about here

Data

We test the proposed hypotheses using patent data and patent citation data from the U.S. patent and trademark office (USPTO). Given that not all inventions are patented and that the economic value of patents that are granted is highly skewed, there is substantial noise in using patents as economic indicators (Griliches, 1990). However, researchers have argued that with careful analysis design and conservative interpretation patent data can be used to learn about innovative activities (Hall, Jaffe, & Trajtenberg, 2002; Pavitt, 1985). Focusing on one product technology in one industry in one country our research design follows this advice.

Since we measure knowledge creation strategies along two dimensions, product technology boundary-spanning and organizational boundary-spanning, these boundaries require careful definition. To define the product technology boundary, following prior research on individual industries (Giarrantana, 2004; Rosenkopf & Nerkar, 2001), we reviewed the manual of the U.S. patent classification system (USPCS) and selected sub-class level patent classification numbers that are relevant to the automotive airbag technology, and cross-referenced them with the manual of the International Patent Classification (IPC). Additional keyword searches and cross-checks with USPTO employees increased the confidence that our sample neither excluded relevant patents nor included non-relevant patents. As a result, our airbag product technology boundary comprises all patents with classification numbers that fall in one of the categories between USPC 280/728.1 and USPC 280/743.2 (Table 1).

Insert Table 1 about here

To be able to recognize knowledge creation as search that can cross organizational boundaries requires dynamically identifying the location of an organization's boundary, i.e., to take into account changes over time through mergers and acquisitions (M&A) or divestments. To do this, we categorized organizational boundary changes into four types (subsidiaries, joint ventures, M&As, and divestitures) and developed rules to decide when a knowledge search process crosses an organizational boundary (Figure 3).

First, a search process between subsidiaries is considered as not crossing an organizational boundary. Second, a search process between a joint venture and its parents is also considered being within the organizational boundary (Oxley & Wada, 2009). Third, a search process between acquired firm and acquiring firm is considered as occurring within the organizational boundary if the search occurs after the acquisition, but across the organizational boundary if the search was conducted before the acquisition. These three definitions are based on the empirical finding that tie strength and trust are positively correlated with inter-organizational knowledge transfer (Van Wijk, Jansen, & Lyles, 2008). Fourth, we consider a knowledge search process between divested part and firm parent as crossing the organizational boundary if a search is made after the divestiture, but within the organizational boundary if a search is made before the divestiture.

Insert Figure 3 about here

We explore knowledge search processes and their impact using prior art citations which a patent makes and future citations which a patent receives, respectively. The citations data we extract from the National Bureau of Economic Research (NBER) U.S. patent citations data file that includes citation data from 1975 to 1999 (Hall et al., 2002) and link it to the detailed patent data using corresponding patent numbers. Figure 4 presents the distributions of patent and citation data for the airbag technology patents.

Insert Figure 4 about here

Because only customers ultimately purchasing an industry's products and services allow an industry to exist, we focus in determining the point of industry emergence on the recognizable beginning of the sales take off. Following Agarwal and Bayus (2002) we define as the sales take-off year the year that exhibits the largest year-on-year sales increase, measured in percent. In our data set, this year is 1990 with annual sales growth of 985%. Based on this definition, we use the year switch 1989/1990 to separate the industry pre-takeoff incubation stage from the industry post-takeoff growth stage. Next, we expand each stage to include six years each, i.e., 1984-1989 and 1990-1995, to cover all major portions of the growth of both knowledge creation activity and product sales.

During our focus time frame from 1984 to 1995, a total of 1,938 patents were filed in this product technology (industry) and of those, 1,825 patents were owned by 180 firms based on adjusted assignee codes (113 patents did not have any assignee code). Those 1,825 airbag patents made 19,518 prior art citations and received 17,781 future citations during our analysis timeframe. Since in our data set 17 firms account for about 70 percent of the total patents and for more than 70 percent of the total citations received, we focus our analysis on these 17 firms (Table 2).

Insert Table 2 about here

Variables

Dependent variable: Invention performance

We measure firms' invention performance using the number of patent citations that the patents of a focal firm receive. Researchers have interpreted the number of citations that a patent receives from subsequent patents as an indicator of the relative importance of the focal patent (Ahuja & Lampert, 2001; Fleming, 2001; Gay & Le Bas, 2005; Rosenkopf & Nerkar, 2001; Trajtenberg, 1990). The correlation between citations received and technological importance is seldom challenged; the correlation between citations received and economic value is less significant as this relationship contains substantially more noise. Thus, we limit our findings conservatively to technological impact. We define impact of a firm i in year t as the number of citations which firm i's patents in year t receive from subsequent patents. A look at the top performing patents shows that the system architecture of automotive airbags was established in the early 1980s, after which the influential work shifted to the component level, first to inflators, then to bags, and then to electronic sensors (Figure 5).

Insert Figure 5 about here

Independent Variable: Knowledge creation

Because in the U.S. each patent must cite prior patents to recognize relevant existing technology, previous research has frequently used patent citations also as a proxy of knowledge flow (Katila & Ahuja, 2002; Rosenkopf & Nerkar, 2001). However, recent research has cautioned the overly optimistic use of patent citations as a proxy of knowledge flow. For example, in a study of patents from 2001-2003 Alcacer et al. (2009) find that between 41% and 60% of all citations have been added by patent examiners. At the same time, while acknowledging substantial noise in patent citation data, Jaffe et al. (2002) find in their survey-based study significant evidence for knowledge spillover related to patent citations, and – employing carefully constructed research designs – recent research continues to use patent citations to study knowledge flow (Jang, Lo, & Chang, 2009; Oda, Gemba, & Matsushima, 2008; Oxley & Wada, 2009).

Applying our boundary definitions introduced above, and building on Rosenkopf and Nerkar (2001) we define four variables to map a firm's knowledge building activity during the focal timeframe into one of four exploration sub-areas: local, internal boundary-spanning, external boundary-spanning and radical. *Local exploration* is measured by the number of prior art citations that do not cross either the product boundary or the organizational boundary, made by a firm *i* in year *t*. *Internal boundary-spanning exploration* is measured by the number of prior art citations that cross the product boundary but do not cross the organizational boundary, made by a firm *i* in year *t*. *External boundary-spanning exploration* is measured by the number of prior art citations that do not cross the product boundary but do cross the organizational boundary, made by a firm *i* in year *t*. *Radical exploration* is measured by the number of prior art citations that cross both the product boundary and the organizational boundary, made by a firm *i* in year *t*.

We also measure the extent of knowledge search with respect to organizational boundary and product boundary independently. The extent of knowledge search with respect to organizational boundary is measured by the number of self citations made by a firm *i* in year *t*, and the extent of knowledge search regarding the product boundary we measure by the number of airbag technology-related citations made by a firm *i* in year *t*.

Figure 6 provides a view on the shifts of the top five patenting firms from 1984-89 to 1990-1995. Note that all firms increase the fraction of within product technology citations between pre- and post sales takeoff, a sign of a maturing technology. The firms differ, however, in the way they build on existing internal knowledge, especially in the pre-sales takeoff phase. The two automobile manufacturers, GM and Daimler-Benz, and the explosives company, Morton Thiokol, bring in substantial own knowledge in the pre-sales takeoff phase, but *decrease* this internal reliance in the post-sales takeoff phase. In contrast, the two suppliers, Takata and TRW, who enter this niche industry without much prior knowledge in airbag technology *increase* their reliance on internal knowledge between pre- and post-sales take off.

Insert Figure 6 about here

Control Variables.

Number of patents: Since the number of citations which a firm receives can be affected by the sheer size of a firm's patent portfolio, we include number of patents to control for this effect.

Other citations: In cases where patents do not contain assignee codes, we cannot decide whether a citation crosses an organizational boundary. We count the number of citations which cannot be assigned to any of the four types of knowledge exploration as 'other citations.'

Patent age: Since patents granted in earlier years are on average more likely to have received more citations only because they have been exposed over a longer time period we include patent age from application to year 1995 as a control.

Number of acquisitions: Acquisitions can be beneficial if the knowledge base of the acquired can be utilized (Ahuja & Katila, 2001) and detrimental if managerial energy is absorbed by the integration process instead of by R&D (Hitt, Hoskisson, Ireland, & Harrison, 1991). To control for these effects we include the number of acquisitions on the subsidiary level.

Region: Knowledge may flow more effectively within national borders than across them due to geographic proximity, cultural similarity, or inventors' mobility (Birkinshaw & Hood, 1998; Krugman, 1991; Stolpe, 2002). We include region dummies which are determined by the geographic location of a firm's head-quarter to account for this potential bias.

Position in supply chain: Although we focus on one industry, its players are not all identical. Research on the automobile industry has shown that the type of relationship between original equipment manufacturer (OEMs) and its suppliers impacts the performance of both OEM and supplier, and of the overall supply chain (Helper, 1991). To account for this effect we include dummies to distinguish between OEMs (0) and suppliers (1).

Model Specification

Since our dependent variable, invention impact as measured by the number of citations received, is an overdispersed count variable, we specify a negative binomial distribution to allow the variance to be greater than the mean (Cameron & Trivedi, 1998; Hausman, Hall, & Griliches, 1984), and employ the Generalized Estimating Equations (GEEs) regression method to account for repeated observations for the same firms over time (Dobson, 2002; Hoffmann, 2004).

Estimation Results

Tables 3 and 4 present descriptive statistics and correlations for all variables, separately for the two timeframes of 1984-1989 and 1990-1995. Because of the additive nature of the four types of exploration variables, we control for total citations and report partial correlations with respect to total citations. Table 5 presents the estimated coefficients for the GEE regression models (Model 1 and 2) for each timeframe. We also report confidence intervals ($p < 0.05$) for the four types of exploration in Model 2 to investigate if they are significantly different from each other.

Insert Table 3 about here

Insert Table 4 about here

Insert Table 5 about here

The Industry Pre-Takeoff Stage (1984-1989)

In Model 1, we consider each dimension independently. As shown in Table 5, the coefficients for both self citation and airbag citation are significant and positive. This result demonstrates that in the industry pre-takeoff stage developing a solution from a firm's own prior knowledge has a greater impact than searching for a solution across the organizational boundary. This finding supports Hypothesis 1A.

Model 2 presents the results considering both dimensions of knowledge relatedness simultaneously and examines the relative impact of the four different types of exploration. We find that internal boundary-spanning exploration and radical exploration obtain significant coefficients, and that the coefficient of internal boundary-spanning is significantly higher than that of radical exploration ($p < 0.05$). This result suggests a firm building on its own prior knowledge but outside of the product technology is most likely to develop high impact technological solutions in the industry pre-takeoff stage, fully supporting Hypothesis 1B.

The Industry Post-Takeoff Stage (1990-1995)

We hypothesized that as an industry shifts from the early incubation stage to a steep growth stage, different capabilities will be required to succeed in this new environment. Our results demonstrate that the impact of different types of knowledge searches indeed changes as the industry emerges. In Model 1, the coefficients for both self citation and airbag citation are significant and negative, which demonstrates that in the industry post-takeoff stage a firm searching for a new solution outside of the firm is more likely to develop high impact technological solutions than a firm building on its own prior knowledge, providing support for our Hypothesis 2A.

In Model 2, while we hypothesized that external boundary-spanning has the highest impact in the industry post-takeoff stage, we find that the coefficient of external boundary-spanning exploration is significantly higher than that of local exploration ($p < 0.05$) but significantly lower than that of radical exploration ($p < 0.05$) and insignificantly different from that of the internal boundary-spanning exploration. This result does not support Hypothesis 2B. We will return to this result in the discussion section.

Of our control variables, number of patents obtains significant and positive coefficients for both Model 1 and Model 2 and for both timeframes. Patent age obtains significant and positive coefficients for both models in the industry post-takeoff stage but insignificant and negative coefficients for both models in the pre-takeoff stage. While patents granted in earlier years are likely to have more citations because they have been available for a longer time period, the value of patents also depreciates over time. Number of acquisitions does not obtain significant coefficient in either stage. Significant (except for region 'Japan' in pre-takeoff stage) and negative coefficients of region dummies suggest there is a discernable disadvantage for foreign firms. Finally, our results do not indicate that the position in the supply chain makes any difference for the firms' technological performance.

Discussion

We hypothesized that the moment of industry emergence changes the relative effectiveness of various knowledge building strategies. Testing our hypotheses empirically with data from the U.S. automotive airbag industry, we find that this change indeed occurs. In the industry pre-takeoff stage knowledge exploration within the organizational boundary has a greater impact on subsequently developed technological solutions than exploration across the organizational boundary. Moreover, the finding of an organization inward focus but an technological outward focus is consistent with earlier research emphasizing firms' absorptive capacity (Cohen & Levinthal, 1990) and adaptive search (Levinthal & March, 1981).

With the shift to the industry post-takeoff stage of the airbag industry the higher impact on subsequent technological solutions now shifts to explorations across the organizational boundary. This result suggests that once the industry sales take off and many fundamental questions have been answered, a focus that is too strong on the firm's own knowledge can result in core rigidities. This finding is in line with other results for mature industries (Rosenkopf & Nerkar, 2001). In addition, we find that in this post-takeoff stage knowledge from outside the product technology has a higher impact than more closely related knowledge. This result cannot confirm our hypothesis 2B, but might be caused by our impact measure measuring overall impact; it is possible that the product technology impact would be influenced more through a knowledge search within the product technology category.[2]

Beyond the detailed results for individual phases, this study produced two important findings. The first insight is that the grounds indeed shift when an industry emerges. This shift in relevance of various knowledge exploration patterns at the birth of the industry signals that a shift in search strategy is required, which, in turn, has implications for R&D management. It has been suggested that firms need to find the balance at the intersection of exploration and exploitation (Lavie, Stettner, & Tushman, 2010) and that they need to account for different dimensions even within the exploration dimension (Rosenkopf & Nerkar, 2001). To complement this body of knowledge we add that these exploration decisions should be different at very early industry life cycle stages.

[2] We were unable to use a product-technology impact measure for comparison across the pre- and post-sales takeoff phases as the dataset is too small in the pre-take off period.

The second insight carries another lesson for R&D management, and more broadly, for corporate entrepreneurship. The results explain why firms with simple, i.e., internal, access to knowledge that is somewhat distant to the original business (e.g., explosives to automobiles) but relevant in a new application (e.g., airbag inflators) have an advantage over de novo firms. Consequently, it is a task for company leaders to identify promising areas to which existing knowledge can be transferred and built upon.

Conclusion

The main contribution of our study is the investigation of the dynamic nature of effective knowledge creation strategies in a technology-intensive industry. We develop the idea, and provide supporting empirical evidence, that knowledge search is not only a multi-dimensional but also a dynamic and context-dependent concept, and that a major shift occurs as the industry moves from an embryonic stage into a growth stage, a change that needs to be actively managed.

There are at least two limitations to our study. First, patent data can only track successful inventions that are patentable. Many process inventions that are not patented are not accounted for in our data set, and, while not patented, these inventions still require active attention of the R&D management. Second, the single-industry context, while allowing to build rich datasets to unearth and analyze interesting relationships and mechanisms (Fixson & Park, 2008; Lee, Veloso, Hounshell, & Rubin, 2010), simultaneously requires caution when extrapolating the results to other settings.

A direction for future research could address this limitation and take our results and tests them in other industries. A second direction could be a study of de novo vs. de alio firms. Such a study could follow Khessina and Carrol (2008) who find in their study of the optical disk drive industry that de novo firms experience a stronger identity imprint through activities in the focal industry compared to de alio firms who experienced their identity formation in other industries. These identity imprints might lead to additional variations in knowledge exploration behavior.

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Tables and Figures

Table 1: U.S. patents class/subclass numbers and titles related to automotive airbags

Level 1	Level 2	Level 3	Title
280/728.1			Inflatable passenger restraint or confinement (e.g., air bag) or attachment
	280/728.2		With specific mounting feature
	280/728.3		Deployment door
	280/729		Plural compartment confinement (e.g., "bag within a bag")
	280/730.1		Inflated confinement specially positioned relative to occupant
		280/730.2	Mounted in vehicle and positioned laterally of occupant
	280/731		Deflated confinement located within or on steering column
	280/732		Deflated confinement located in or on instrument panel
	280/733		In the form of or used in conjunction with a belt or strap
	280/734		Responsive to vehicle condition
		280/735	Electric control and/or sensor means
	280/736		With source of inflation fluid and flow control means thereof
		280/737	With means to rupture or open fluid source
		280/738	With means to aspirate ambient air
		280/739	With confinement deflation means
		280/740	With means to diffuse inflation fluid
	280/741		Inflation fluid source
	280/742		Flow control means
	280/743.1		Specific confinement structure
		280/743.2	With confinement expansion regulating tether or strap

Table 2: Top 17 firms and their distribution of patents and firm-years

Firm	Number of patents	Cumulative percentage	Number of years
TRW	325	16.2	10
MORTON THIOKOL	262	29.3	12
TAKATA-PETRI	180	38.3	8
GENERAL MOTORS	116	44.1	9
DAIMLERBENZ	70	47.6	10
TOYOTA MOTOR	63	50.7	9
TEXTRON	60	53.7	7
FORD MOTOR	53	56.4	8
ROBERT BOSCH	46	58.7	11
ALLIEDSIGNAL	45	60.9	7
TOKAI RIKA	41	63.0	9
HONDA MOTOR	37	64.8	10
BREED	35	66.6	11
NISSAN MOTOR	30	68.1	9
DENSO	25	69.3	6
DYNAMIT NOBEL	17	70.2	7
AUTOLIV ASP	17	71.0	3
Sum	1422		146
Total	2002		831

Table 3: Descriptive statistics for the timeframe 1984-1989

Partial Correlation Coefficients, N = 49

	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11
1. Total Impact	61.41	72.85	1.00										
2. Self Citations	2.86	4.67	0.28 .	1.00									
3. Airbag Citations	14.98	15.65	0.31 *	-0.29 *	1.00								
4. Local	1.98	3.03	0.19	0.92 ***	-0.21	1.00							
5. Internal	0.88	2.02	0.32 *	0.82 ***	-0.32 *	0.53 ***	1.00						
6. External	13.00	14.24	0.17	-0.63 ***	0.91 ***	-0.60 ***	-0.49 ***	1.00					
7. Radical	5.37	8.46	-0.36 *	-0.11	-0.69 ***	-0.10	-0.09	-0.53 ***	1.00				
8. Others	1.92	4.08	-0.27 .	0.14	-0.65 ***	0.16	0.07	-0.60 ***	0.03	1.00			
9. Number of Patents	2.88	2.60	0.54 ***	-0.11	0.38 **	-0.14	-0.04	0.37 **	-0.42 **	-0.11	1.00		
10. Patent Age	8.59	1.54	0.09	0.06	-0.20	-0.06	0.22	-0.14	0.19	-0.03	-0.13	1.00	
11. Number of Acquisitions	1.18	1.59	0.14	-0.26 .	0.20	-0.15	-0.34 *	0.22	-0.08	-0.03	0.02	0.04	1.00
12. Total Citations	23.14	26.94	.	.	.	.	.	.	.	.	.	.	.

(Significance code: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1)

Table 4: Descriptive statistics for the timeframe 1990-1995

Partial Correlation Coefficients, N = 97

	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11
1. Total Impact	95.06	124.21	1.00										
2. Self Citations	19.21	44.65	-0.52 ***	1.00									
3. Airbag Citations	99.01	188.72	-0.11	0.01	1.00								
4. Local	17.30	40.52	-0.45 ***	0.96 ***	0.19 .	1.00							
5. Internal	1.91	5.12	-0.33 **	0.23 *	-0.66 ***	-0.03	1.00						
6. External	81.71	150.00	0.20 .	-0.63 ***	0.76 ***	-0.49 ***	-0.56 ***	1.00					
7. Radical	19.01	38.09	0.01	0.06	-0.93 ***	-0.11	0.63 ***	-0.75 ***	1.00				
8. Others	4.75	10.22	0.48 ***	-0.26 **	-0.53 ***	-0.27 **	0.00	-0.29 **	0.23 *	1.00			
9. Number of Patents	1.97	1.03	0.50 ***	-0.33 **	0.15	-0.26 **	-0.28 **	0.31 **	-0.16	0.06	1.00		
10. Patent Age	3.45	1.70	0.45 ***	-0.03	-0.14	-0.03	0.02	-0.10	0.07	0.23 *	-0.04	1.00	
11. Number of Acquisitions	0.43	0.71	-0.08	0.10	0.02	0.08	0.07	-0.04	-0.04	-0.02	0.11	-0.03	1.00
12. Total Citations	124.68	237.78	.	.	.	.	.	.	.	.	.	.	.

(Significance code: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1)

Table 5: GEE regression coefficients for pre-takeoff and post-takeoff timeframes

	Industry pre-takeoff stage (1984~1989)				Industry post-takeoff stage (1990~1995)			
Variables	Model 1		Model 2		Model 1		Model 2	
Self Citations	0.0770	**			-0.0059	***		
Airbag Citations	0.0440				-0.0221	***		
Total Citations	-0.0373	.			0.0134	***		
Other	0.0169		-0.0053		0.0061		0.0196	***
Local[†]			0.0384 (-0.0452, 0.1220)				-0.0143 (-0.0183, -0.0104)	***
Internal[†]			0.1101 (0.0470, 0.1732)	***			-0.0010 (-0.0339, 0.0318)	
External[†]			0.0127 (-0.0164, 0.0417)				-0.0085 (-0.0120, -0.0049)	***
Radical[†]			-0.0448 (-0.0869, -0.0027)	*			0.0146 (0.0042, 0.0250)	**
Number of Patents	0.1922	***	0.1597	***	0.0959	***	0.0936	***
Patent Age	-0.0013		-0.0710		0.2630	***	0.2617	***
Number of Acquisitions	0.1008		0.1068		-0.0412		-0.0271	
Region 0 (U.S.)	0		0		0		0	
Region 1 (Europe)	-0.5803	.	-0.6350	.	-0.5556	*	-0.5393	*
Region 2 (Japan)	-0.2152		-0.3658		-0.5922	*	-0.5568	.
Supply-position 0	0		0		0		0	
Supply-position 1	-0.0358		-0.0824		-0.0045		-0.0121	
Intercept	3.3024	***	4.0268	***	2.9273	***	2.9200	***
N	49		49		97		97	
Overdispersion Parameter	5.3559		5.2880		5.1675		5.1870	
Scaled Deviance	35.3714		34.6462		85.1873		84.4778	
Log Likelihood	365.91		376.18		1404.17		1393.70	

(Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1)

[†]: We report 95% confidence interval for estimated coefficients of four types of knowledge exploration to compare if the differences are significant

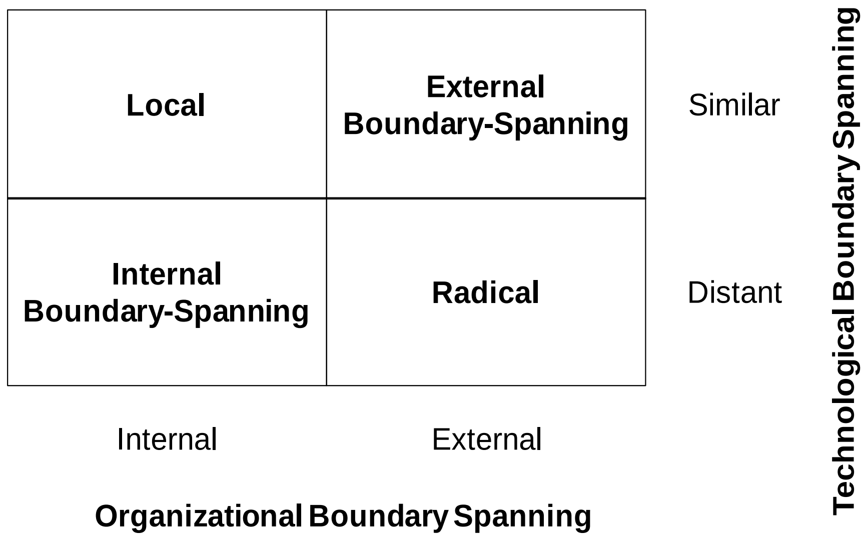

Figure 1: Four types of exploration (adapted from Rosenkopf and Nerkar, 2001)

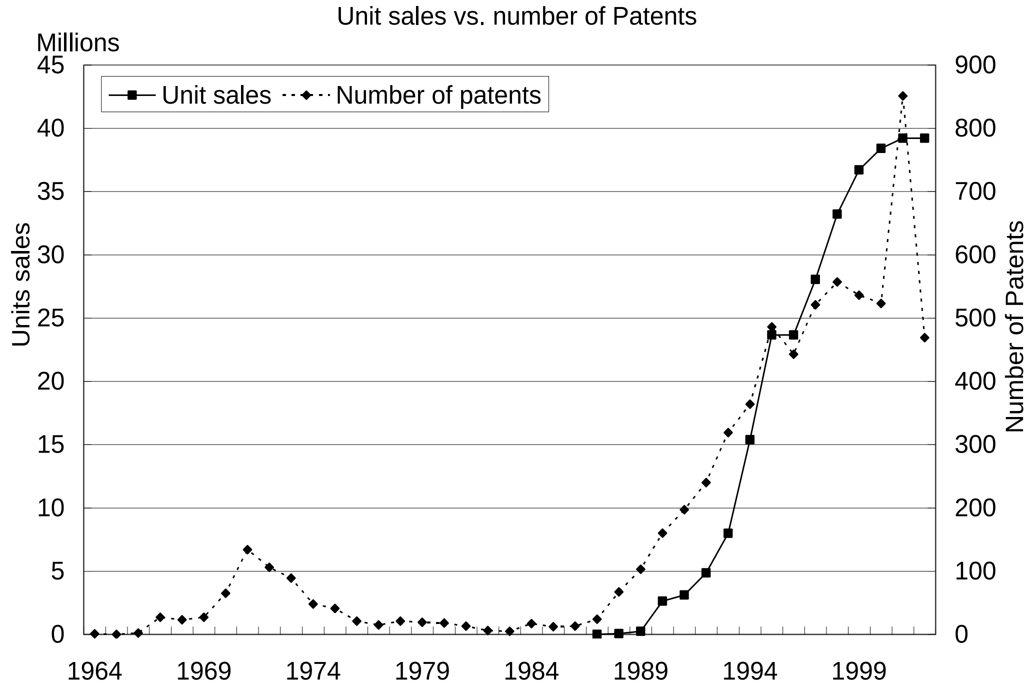

Figure 2: U.S. Automotive airbag patents and market growth (1969-2002)

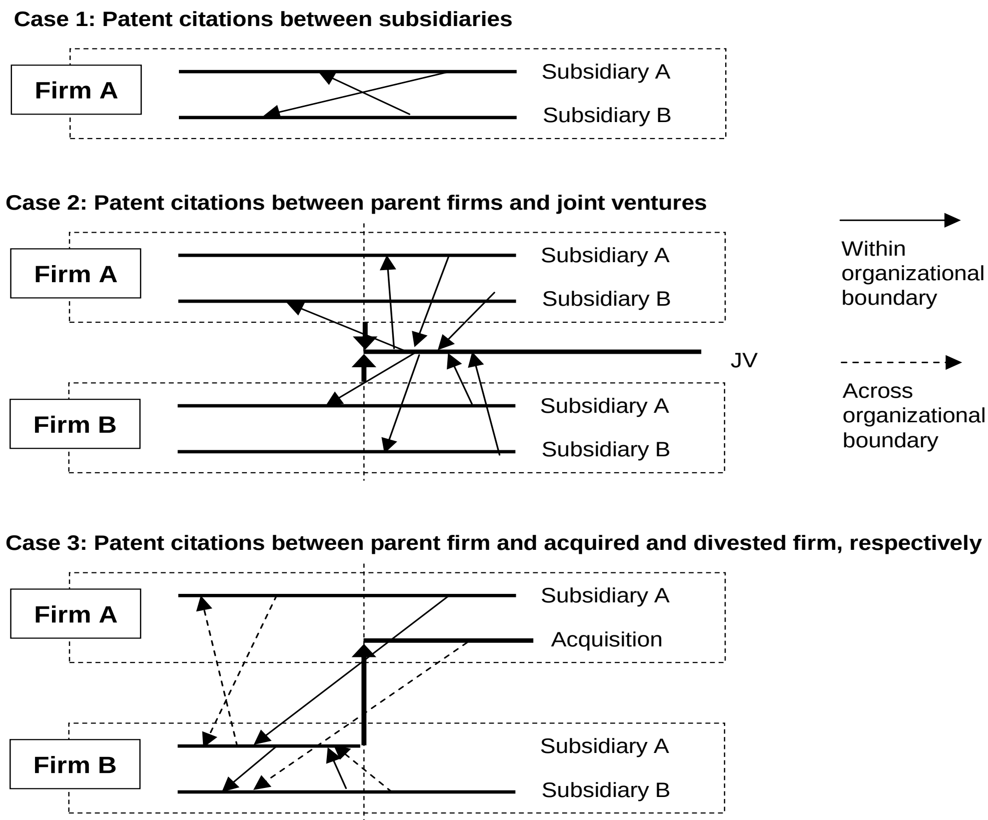

Figure 3: Decision rules for deciding whether a knowledge search crosses organizational boundaries

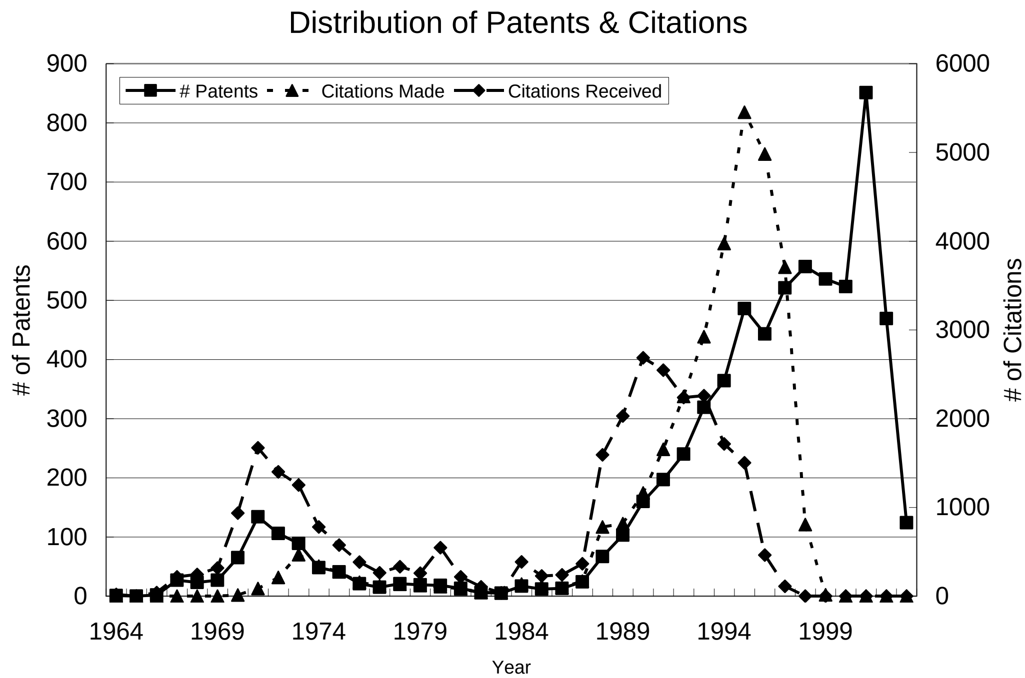

Figure 4: Distribution of U.S. airbag-related patents and patent citations (1964-2002)

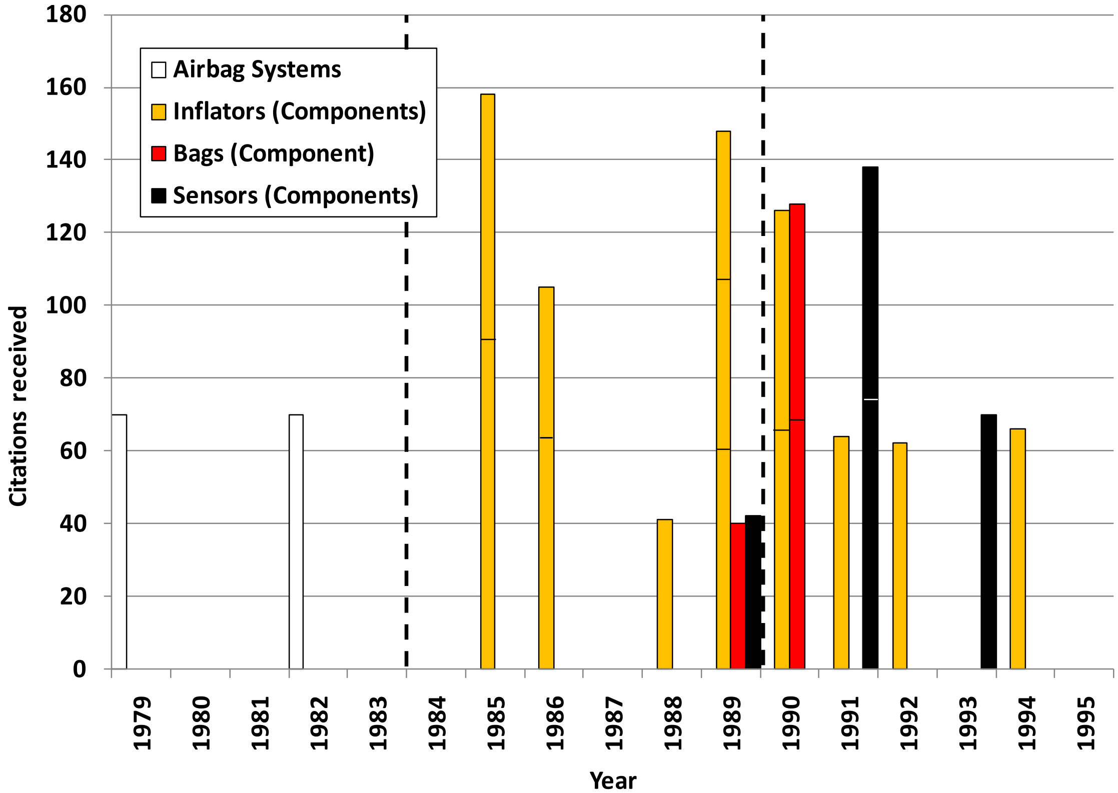

Figure 5: Impact of top-ten patents for 1984-1989 and 1990-1995, and top two patents prior to 1984

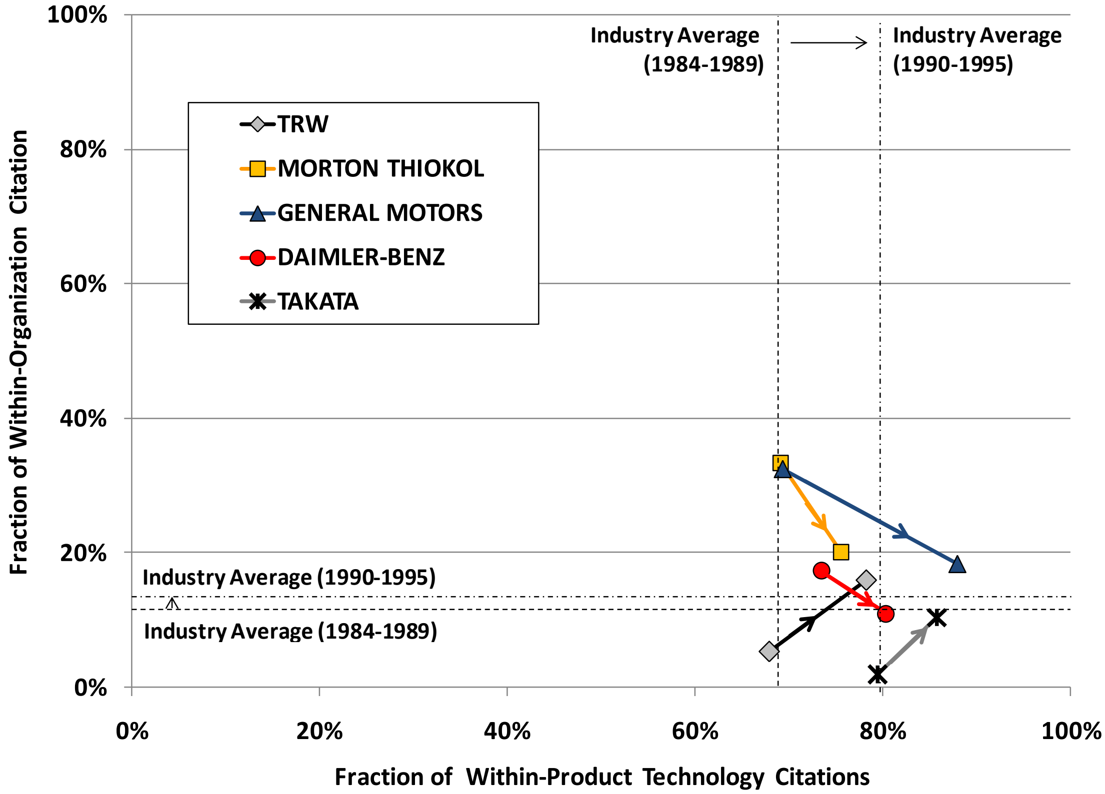

Figure 6: Shift in knowledge creation strategies of top five firms (comparing averages 1984-1989 and 1990-1995)