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R&D Expenditure in a Competitive Landscape: A Game Theoretic Approach

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Abstract

A firm's R&D (Research & Development) expenditure is dependent on the competitive environment and the industry structure it operates in. The purpose of this paper is to understand the drivers of a firm's R&D that are related to the industry structure and to predict the nature of R&D expenditure incurred by firms in different scenarios. We scroll through the extant literature on various game theoretic models related to R&D expenditure in different contexts before coming up with a conceptual model that can be tested and developed further. We anticipate this framework can be useful to understand as well as to forecast the R&D spending pattern at the level of individual firms and for a whole industry. Apart from its contribution to literature, we also discuss some prospective managerial and policy implications of this model.

Keywords: R&D (Research & Development); Industry Structure; Conceptual Model; Game Theory; Symmetric Model; Asymmetric Model.

JEL classification: C79; L13; O32; O39.

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1. Introduction

Innovation has become a requisite for survival in almost all industries (Ortiz-Villajos and Sotoca 2018, Sharma 2017, Wojan, Crown and Rupasingha 2018), let alone to gain and sustain competitive advantage, especially as firms are facing a rapidly increasing dynamic and competitive environment and changing macro-economic conditions. Firms are hence forced to invest in R&D to achieve their innovation targets (Kishi 2018) either as defensive strategies to maintain and/or extend competitive edge over rivals, or as offensive strategies to leapfrog the

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competition and/or sustain competitive advantage, especially during the introductory and growth stages of industry life-cycle (Atallah 2009). There also exists empirical evidence suggesting R&D intensity amongst firms leads to better profit margins (Andras and Srinivasan 2003).

A firm's R&D expenditure depends on the competitive environment it operates in and this is influenced by several factors. The most critical determinant is the industry structure (Neuhäusler, et al. 2017). Factors such as maturity of the industry (Bloch 2018), concentration within the industry, competitive positioning of firms, the entrance of new players, mergers and acquisitions in the industry, firm's interest in maintaining monopoly power, events such as major technological breakthroughs, disruptive technologies, network density (Teng, et al. 2016), the operating patent regime (Dey 2016, Sharma, et al. 2018), strategic alliances (Cumming and Macintosh 2000), and policy interventions (Rahman, Ali, and Ali 2016), can all have implications on the research expenditure of companies.

This paper is structured as follows. Firstly, in the literature review section, we discuss and summarize some of the prominent conversations covered in the existing literature that has tried to explain R&D spending of firms in varying industry structures and scenarios. We discuss some of the practical situations and inconsistencies that restrict using any single model for R&D spending patterns for varying scenarios.

We then propose a conceptual model for R&D spending of firms in different industry structures consolidating the prevailing conversations to fit various game theoretic scenarios. Our conceptual model categorizes a particular competitive scenario by looking at the industry-level data. The key to predicting R&D expenditure is that one must fit advanced models to industries by identifying objective parameters that can help classify patterns of R&D spending in the industry. Once an industry has been classified based on different characteristics, we hope this model could be a good starting point to gain insights on future spending patterns, to identify possible future strategies of target firms, and to simulate possible scenarios such as the entrance of new players, and mergers and acquisitions.

We expect this conceptualization to be valuable from a research perspective, as firstly it proposes a ready framework that can be put to test in varying industry contexts, and it sets a foundation for future researchers to work on. Our model has varying practical applications, for firms trying to predict their competitor movements, for firms to devise own R&D strategies, and also for those firms providing services in the patent industry. We also expect this to help regulators in their intervention policies in certain industries and sectors with a better understanding as a result of the predictive capability provided by this conceptual model.

2. Literature Review

R&D spending, also termed as R&D races are often modeled in game-theoretic scenarios such as 'all-pay auction models' (Baye, Kovenock, and Vries 1996). Application of game theory on R&D spending in industries has close relations to auction mechanisms, including the all-pay auction model or competitive bidding models (Milgrom and Weber 1982).

Some of the earliest discussions on game-theoretical models on R&D spending (Dasgupta 1986, Loury 1979, Rosenkranz 1995) present a simplistic relation to R&D spending in a patent regime. Here, a symmetric *n*-firm situation is considered and R&D expenditure by a firm is considered as a one-time investment, and innovation happens at a time 't' that is an exponentially distributed random variable with the meantime being a function of the amount spent on the research by the firm. The firm that comes up with the innovation first is granted patent over the technology and gets the exclusive right to benefit from the patent. In this scenario, with an increase in the number of firms participating, the individual expenditure for each firm declines while the total industry spending increases.

In a slightly different approach to the previous model, some scholars (Jinji 2003, Lee and Wilde 1980) deem R&D expenditure to be a continual expense incurred by the firm. Here, again in a symmetric *n*-firm situation, the R&D expenditure is considered as a flow expense, rather than as a one-time investment, that a firm incurs in every time interval till the innovation is captured by any one of the players, and the likelihood of a firm capturing the innovation is directly proportional to its expenditure in that period. The conclusions drawn from this model are similar to the one-time expense model except that the rate of investment on R&D for a firm increases with an increase in the number of firms participating in the race although the total spending of the firm would decrease as the expected time to innovate goes down.

Scholars (Breitmoser, Tan, and Zizzo 2010, Reinganum 1981) have also looked upon slightly advanced models for flow spending in R&D as they explain the contradiction between one-time spending and flow cost models in their output in relation to the change in the expected time of innovation with an increase in the number of firms. Fixed cost models predict that the expected time for an innovation would increase when firms are added to the race as the individual spending of each firm declines, while flow cost models predict that the expected time to innovate would decrease as the individual flow spending of each firm increases with added competition.

All the above models assume a symmetric situation, i.e. firms are assumed to be similar and equally capable of coming up with an innovation for a given level of R&D expenditure. However, as examples of such industries are rare to find, we need to look at game theoretic models where players are endowed asymmetrically. Asymmetries can be due to several factors such as skewed market share breakup in an industry (Guerzoni 2010), a leader-competitor scenario in an industry (Freeman 1982), monopolistic or duopolistic conditions in the market (Hattori and Tanaka 2018), R&D capabilities of different players (Ishii 2017, Joshi and Vonortas 2001), etc. Several scholarly discussions (Choi 1996, Christensen 2013, Freeman 1982, Spencer and

Brander 1983, Ungern-Sternberg 1980) had considered asymmetric scenarios. Some insights that can be drawn from such discussions are:

- The magnitude of an innovation and the likelihood of that being invented by industry leaders is inversely related.
- Incumbents invest more than a challenger when innovations are minor.
- The lower the investment in R&D for a large incumbent and its challengers, the greater would be the flow of current revenue to the incumbent.
- The rate of individual firm investment on a particular innovation decreases with the number of expected subsequent innovations.

Some scholars (Freeman 1982, Ungern-Sternberg 1980) have discussed one-time spending investments happening when a leader is having a significant advantage over their rivals. As discussed above, in such asymmetric scenarios, the leader always has an edge in continual incremental innovations that forms the bulk of innovations in an industry, whereas the competitor gets an edge for radical innovation scenarios (Christensen 2013). Free cash flow among dominant players can be an indicator to identify the existence of a few dominant players or leaders in the industry (Baskin 1987, Fairchild 2010).

All the above discussions assume the innovation process to be a stochastic event. However, there are cases where an incumbent player can have a significant advantage over other players in R&D processes and in such cases, the process of innovation is no longer stochastic but deterministic (Campisi, Mancuso, and Nastasi 1997, Salant 1984). Scholars (Gilbert and Newbery 1982) have argued that in such a scenario the dominant firm would continue as a monopolist as it would preempt other firms by patenting innovations.

Another aspect of practical interest in the field of patents is the behavior of firms when licensing is practiced in the industry (Chung and Lee 2015, Yi 1998). The incentives for licensing are categorized as ex-post incentives and ex-ante incentives (Gallini 1984, Gallini and Winter 1985). In a scenario where ex-post licensing is permissible, the most efficient firm would patent the innovation regardless of whether it is an incumbent player or not.

Indicators to a symmetric or asymmetric situation in an industry can be found using industry concentration data. If there is a low or moderate concentration in the industry, it is assumed to have a symmetric situation where all firms compete with each other in R&D and innovation (Almazan and Molina 2005). However, increasing concentration can be an indicator of asymmetric situations where one or a few dominant firms have a definitive edge over other competitors (Anagnostaki and Louri 1995).

Further, patent distribution can be taken as an indicator for fixed-cost and flow-cost spending. In general, process improvements require significant one-time investments (Cohen and Klepper 1996), and if an industry largely pursues process patents, it can be extrapolated to have fixed-cost spending. On the other side, if there are more product patents, this industry can be assumed to have flow-cost spending in R&D expenditure. There also exists empirical evidence on concentration in an industry to be positively related to process patenting but not to product patenting

(Lunn 1986).

A summary of the prominent game theoretical models discussed above can be found in Table 1.

Table 1. Summary of Various Game Theoretical Models Discussed in the Literature

	Symmetric Models		Asymmetric Models	
Model	Fixed Cost Symmetric	Flow Cost Symmetric	Leader Competitor	Licensing Model
Industry	Symmetric *n*-firms	Symmetric *n*-firms	Extendable 2-firm model	Extendable 2-firm model
Spending	One Time	Flow	One Time	Variable Flow
Innovation	Stochastic	Stochastic	Stochastic	Deterministic
Pioneer Literature	(Loury 1979) (Dasgupta 1986)	(Lee and Wilde 1980) (Reinganum, 1981)	(Ungern-Sternberg 1980) (Freeman, 1982)	(Gilbert and Newbery 1982) (Gallini and Winter 1985)

All these theoretical models provide a basis by which we can understand the behavior of firms in industries and their responses to different competitive scenarios. However, many departures can be observed in practice that needs to be taken care of while predicting a firm's actual spending on R&D.

Among the different reasons for such departures, the most important one is that some of the assumptions implicit in the models might not hold in real life (Kaiser 2002). For example, in the case of the symmetric *n*-firm scenario, the expected payoff from a certain innovation was assumed to be the same for all firms. In practice, we would expect different firms to have different expected payoffs and value the market potential of innovations differently and hence they would expend different amounts for the same innovation. As firms possess unique profiles and strategic resource endowments, there could exist competitive asymmetry as any given pair of firms may not pose an equal degree of threat to each other (Chen 1996). There could also be instances when firms underestimate the competitive reaction from incumbent players (Zajac and Bazerman 1991). This can lead to over-optimistic projections and excessive industry capacity in R&D.

We must also keep in mind another simplification in *n*-firm scenarios where we assume that all players enter the game at the same time. This is rarely the case in practical situations as players generally enter an industry with random time gaps in between. Stepladder simulation models can be used in such scenarios, but, in general, the inputs to such simulation models are so abstract that publicly available industry information is not sufficient to justify their application.

3. Conceptual Model

The methodology proposed here for implementing a system that utilizes game theoretic models to predict R&D spending looks at various characteristics of the firms and the industry. The first stage involves the identification of industry boundaries. In certain cases, this might be straight-forward where all firms are completely involved in a particular technology or in the production of a single range of products. For instance, SAP and Oracle virtually compete in the same domain, so is the case with various automobile manufacturers, etc. In other cases, however, the classification might not be very straightforward. For example, P&G and Johnson & Johnson could be competitors in baby care, but P&G might be absent or might have only a marginal presence in the medical device industry. It is, therefore, necessary to follow some standard industry classifications such as, for instance, the Standard Industrial Classification maintained by the U.S. government (Securities and Exchange Commission 2018).

After industry classification, the market share data needs to be analyzed to discover the industry concentration (C.-Y. Lee 2005). This can be achieved by measuring the concentration ratios using the HHI or Herfindahl-Hirschman Index (Department of Justice 2018, Liston-Heyes and Pilkington 2004)). Industries with an HHI between 1000 and 1800 are moderately concentrated, whereas those above 1800 indicates a highly concentrated market (Han, Zhang and Greene 2017). A moderate or lower concentrated industry can be modeled as a symmetric n-firm game as industry participants can be assumed to be equally endowed, while a highly concentrated industry can be modeled as a leader-competitor or a licensing scenario to explain the asymmetry. Indicators such as free cash holdings of firms and other financial indicators can be used to understand monopolistic power (Almazan and Molina 2005).

Another aspect to be considered is the R&D spending pattern in the industry, as there are considerable differences between flow spending and one-time spending models. As this information might be difficult to gather, an approximation can be made by analyzing previous patent activity in the field. In general, cost-cutting spending characterizes one-time R&D expenditure (Spence 1984). So, for practical implementation, the patent landscape in the industry can be analyzed and if the patents are predominantly process patents then a fixed cost model can be applied while flow cost models can be used for industries where a majority of patents are product patents (Weiss 2003).

Finally, it is also necessary to determine if the innovation process is primarily stochastic or deterministic. It is suggested that the patents in the sector can be classified company-wise and the Gini Index for the patent distribution be calculated (Behdani, Borzadaran and Gildeh 2018). In case the distribution is highly skewed then it means that one or more firms have a definite edge in terms of R&D and would be expected to dominate the R&D space in related fields, while the competitors would focus on innovations with greater magnitude. Licensing models can be applied when considerable differences exist between market shares of the players and their patent portfolios.

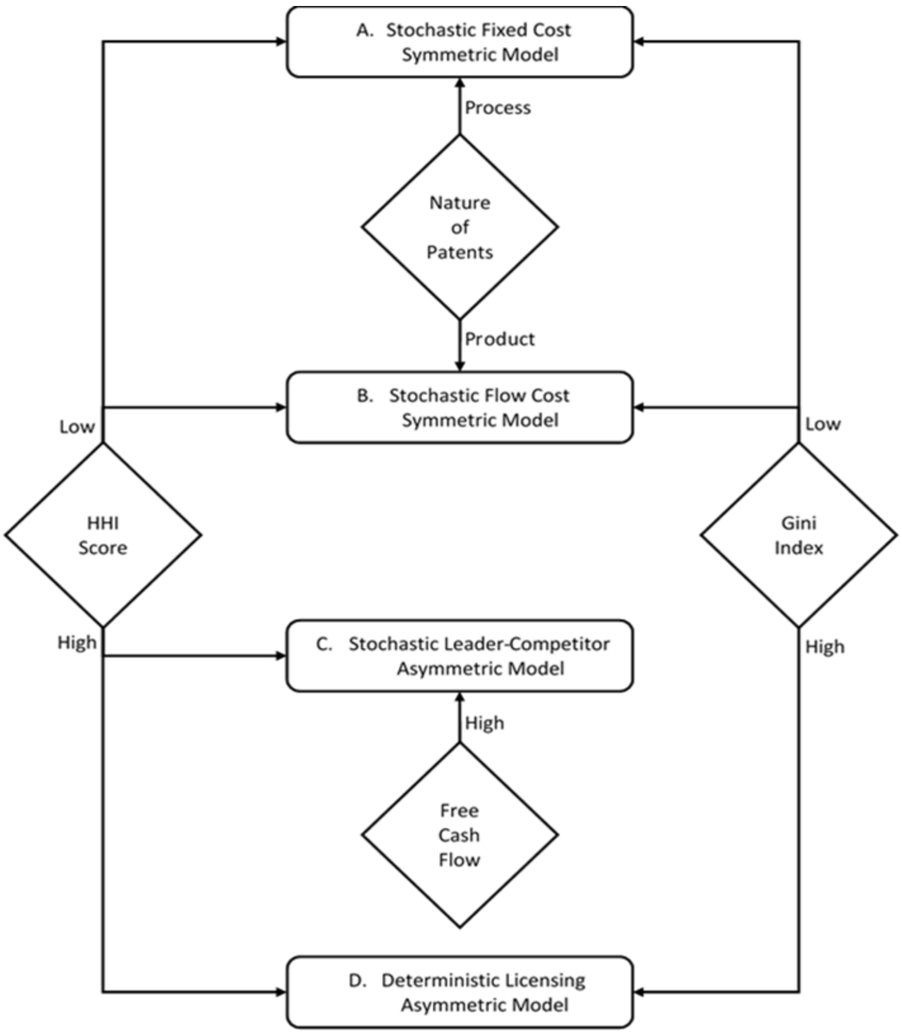
A summary of the above identification characteristics can be found in Table 2.

Table 2. Summary of Industry Characteristics Identification Steps

Industry classification information such as the U.S Standard Industrial Classification
Market share information in various industries
Financial information of the companies in the industries of interest
Patent count information for companies in the industry
Historical R&D spending data and historical patent filing dates

With the above classifications made, the most apt model can be selected and applied to the industry. The model can then be used to predict future R&D spending patterns in the industry. The insights gained can be further used for quantitative as well as qualitative analysis. For instance, regressive models can be combined with the predictions to come up with future R&D spending estimates for individual players. The firms that will spend the most on R&D and the direction of the spending can be estimated to some extent. For example, when a leader-competitor model is identified, we know from the model that a competitor would have to spend more on R&D, but its focus would be on delivering greater innovation while a leader will direct its R&D expenditure on delivering smaller innovation. The R&D spending can also be linked to market potential data for nascent industries where the models give intuitive relationships between the payoffs and firm spending. The proposed conceptual model is depicted in Figure 1.

Figure 1. Conceptual Game-theoretic Model for R&D Spending in Competitive Industries



Block A and Block B of the conceptual model represents a scenario where both HHI and Gini Index scores are low. As discussed previously, we anticipate a low HHI score or lower concentration in the market as an indicator for a symmetric pattern in the industry. A low Gini score indicates patent distribution is not skewed and hence all market participants have almost equal chances of achieving a stochastic innovation output. To identify whether R&D spending in a given industry follows a fixed cost model or flow cost model, we propose to use the nature of patents in the industry. If there are more process patents, we suggest it could belong to fixed cost spending pattern as given in Block A, and if there are more product patents it can represent a flow cost spending pattern and hence Block B.

Coming to Block C and D, we take higher market concentration or high HHI score as an indicator for an asymmetric pattern in the industry. In such a scenario, if we find a high free cash flow among the leading participants, we propose a leader-competitor model, which is depicted by Block C. On the other side, if we find a high Gini Index score, it can be interpreted as a skewed patent distribution which leads to a deterministic model that can be found in a licensing model, or the one represented by Block D.

4. Discussions & Conclusions

This paper is an attempt to look at the drivers for R&D spending in an industry. The theoretical understanding to predict the R&D expenditure in a given competitive environment is essential as individual firm-level data might not yield enough information to build the overall picture needed to understand the dynamics involved. Understanding the scenario at an industry-level by listing the actors and their possible strategic intentions can give a sound basis to build a competitive strategy for firms within an industry. It can also help to design advanced CRM systems for providers of third-party services that can recommend sales pitches and help providers of competitive services that manage relationships with their customers.

We hope this conceptual model could be useful for a service provider such as a patent services firm to gain insights for tailoring their services that can be offered to different clients based on their requirements. For example, a patent advisory might offer litigation-based services to industries with heavy concentration or steady patent activity while it would offer landscaping and patent buyout advice to monopolistic scenarios.

Another potential use of the model is to answer what-if questions. The model gives insights into changes in R&D spending with events such as increases and decreases in the number of participating firms that can be used to simulate changes that can be expected with takeovers, mergers, or entrance of new players into the industry.

Patterns that are learned from studying one industry can be carried forward to improve the regressive estimates in other industries and to fine-tune the cutoffs used for the classification. The learning from comparing scenarios predicted by these models can be used by firms to adapt their R&D strategy to changing industry conditions and also to discover competitive blind spots such as excessive spending in R&D vis-à-vis the competition.

We also expect our model to be useful for policymakers to gain a better understanding of R&D spending in various industries and thus gives them a platform to judiciously intervene in industries and sectors with the aid of predictive capabilities provided by the model.

Meanwhile, we do not argue that the model in the present conceived form would accommodate all practically occurring scenarios. One such shortcoming is in accommodating the recent trends in open innovation or coopetition amongst industry participants. There are cases where firms open up their innovation adventures to collaborate with external participants instead of restricting to own R&D resources (Segarra-Ciprés and Bou-Llusar 2018), or engage in coopetition or simultaneous pursuit of competition and cooperation especially in knowledge-intensive industries leading to radical innovation at times (Bouncken and Kraus 2013, Quintana-García and Benavides-Velasco 2004), however, our model doesn't address such scenarios.

A major challenge in the analysis of R&D spending and the impact of industry concentration is the isolation of the effects of strategic decisions based on the competitive environment and other factors that also drive firms to invest in R&D such as accelerated adoption of new technology. Studies have found a positive correlation between R&D spending and revenue growth across sectors among S&P 100 firms (Craft 2018). CEO characteristics such as executives' academic specialization and areas of management experience are also believed to have a strong impact on firms' R&D spending (Gwynne 2003). Other factors such as firm size (Kim, et. al. 2009) corporate financial autonomy, enterprise revenue & profitability, higher enterprise goodwill, and better human resources are all found to have a bearing on R&D investment activity (Lai & Lin 2015).

In the U.S., between 2007 and 2012, the market concentration increased rapidly in the financial sector, while remaining relatively constant in manufacturing in the same period (Hamilton 2018). However, R&D expenditure across financial and insurance activity grew by 200% (outgrowing revenues), while staying relatively constant in manufacturing from 2008 to 2012 (OECD 2019). This indicates that the analysis of R&D spending patterns over a short duration of time may be dominated by factors other than those outlined by the competitive landscape models. A deeper analysis of the patterns must identify a robust industry classification model, which can then be used to classify firm and their R&D spending across multiple markets and over a long duration of time. More analysis is also needed to isolate the variations in R&D spending arising from non-strategic aspects outlined in the previous paragraph.

However, we hope that data resulting from the preliminary application of this model may be helpful in the construction of more practical models that can simulate multiple competitive scenarios. Being one of the very first attempts on conceptually understanding various industry scenarios and their implications on R&D spending of firms, we hope this model sets a foundation for both future researchers and practitioners to dig deeper, revise, and develop better predictive models.

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