Communications in Mathematics and Applications
Vol. 14, No. 5, pp. 1889–1907, 2023
ISSN 0975-8607 (online); 0976-5905 (print)
Published by RGN Publications
DOI: 10.26713/cma.v14i5.1925

http://www.rgnpublications.com

Review Article

International R&D Partnerships Between Companies: A Computational Study

Mohamad Alghamdi

Department of Mathematics, College of Sciences, King Saud University, P. O. Box 2455, Riyadh 11451, Saudi Arabia
almohamad@ksu.edu.sa

Received: June 3, 2022 **Accepted:** October 2, 2022

Abstract. This paper contributes to the empirical study of the cooperation of companies in research and development (R&D). The contribution is based primarily on the consideration of all industrial sectors under all types of agreements at the domestic and international levels. The outcomes suggest that active companies in the cooperation system played an important role in forming overlapping structures. In particular, the cooperation of those companies included domestic and international agreements and served multiple sectors.

Keywords. R&D partnerships, Economic development, Organizational identity

Mathematics Subject Classification (2020). 62P20, 91B82

1. Introduction

The cooperation of companies in the world takes different forms to achieve specific objectives. One of these forms is the investment of companies in R&D that has become an essential component of the innovation process. The innovation leads to productive and industrial development, which in turn encourages companies to continue production in a competitive market. The innovation process does not only depend on single companies but on a group of companies that conform in a particular way and perhaps in a certain period to develop their products (Belderbos *et al*. [3], Hagedoorn and Schakenraad [15], Nooteboom [27], and Silipo [31]). The authors noted the importance of cooperation in the exchange and classification of knowledge

and resources. The process of investment in R&D and identification of partners depend on the demands of the companies and expertise necessary to develop their industrial status (Caloghirou *et al*. [4], Eerola and Määttänen [10], López [22], Narula [26], and Vonorts [35]).

Many authors have shown the great role played by companies' cooperation in R&D, e.g., Kobayashi [19], Petrakis and Tsakas [28], Silipo [31], and Zhou *et al*. [40]. Improving and increasing products and reducing production costs are key objectives of companies' cooperation. In addition to reducing the value of investments that decrease with the increase of the number of cooperative agreements that include many companies (Alghamdi [1], Goyal and Moraga-Gonzalez [12], and Silipo [31]). However, there are obstacles that may limit the benefit behind investments and cooperation of companies in R&D; for example, transaction cost and knowledge flow (R&D spillovers).

These issues related to the cooperation of companies in R&D have attracted us to undertake an empirical study concerning the participation of companies worldwide in this field. We use the CATI Database, developed by J. Hagedoorn and M. van Ekert [16] at the University of Maastrich. We provide a statistical description of the cooperation of companies in R&D over twenty years from 1981 to 2000. We consider a general framework covering all types of R&D agreements for domestic and international contracts concluded in that period in all industrial sectors. In contrast to other studies, which are concerned with some sectors or certain types of R&D agreements (e.g., Hagedoorn and Schakenraad [15], Hernán *et al*. [17], Röller *et al*. [29], and Silipo [31]). According to the database, the industrial sectors are classified into four technological fields: biotechnology, information technology, new materials technology and not core technology.

The results of the present paper can be summarized as follows. First, there was massive growth in R&D cooperation during the last two decades of the twentieth century. The growth includes the number of companies participated in R&D and number of R&D agreements. The study shows that American companies had a great role in this increase, followed by British and Japanese companies. This conclusion is consistent with Hagedoorn and Schakenraad [15] who found that cooperation in the information and communication technology industries in the 1980s was based on seven companies, mostly from the United States and Japan. However, the increase in R&D alliances was small compared to the number of cooperating companies. Transaction costs related to inter-firm agreements may be one of the causes of declining R&D alliances (Desai *et al*. [9], and Silipo [31]).

Second, not core technology and information technology were the most participatory field over the last two decades of the twentieth century. Further analysis reveals that in not core technology field, the majority of participants were in the automotive and chemical sectors; whereas the minority were in the exploration, drilling, medical and space technology sectors. In the information technology field, the highest rate of cooperation was in the telecommunications sector, while cooperation in computers and miscellaneous sectors was the smallest. In the other fields, we found that agricultural biotechnology and pharmaceuticals were the most active sectors in biotechnology. In the new materials technology, we find that the majority of the participants were in the sector of electro, magnet and optics.

Third, there were overlaps between the four technological fields. In the sense that there were companies engaged in R&D for more than one field. For example, Mitsubishi, which is a Japanese company, collaborated during the study period in the four technological fields with many other companies. There are other companies that participated in at least two fields, such as Philips and IBM. These companies were the most cooperative companies in the entire study period. The diversity of the cooperation reflects the positive effects gained from the establishment of several collaborative agreements.

Finally, the R&D partnerships between companies were conducted under different forms of agreements. According to the database, there are 11 forms of R&D agreements. In the early to mid-1980s, most agreements took the form of licensing, then joint development agreements in second place, followed by joint ventures and minority holding. After that period, most of the cooperation was in the form of the joint development agreements, followed by the joint ventures. Other forms such as standards, research corporation, mutual second sourcing and cross holding were the least used.

The paper also discusses the consistency of our empirical results with the theoretical results of R&D cooperation (e.g., Alghamdi [1], D'Aspremont and Jacquemin [7], Deroian [8], Goyal and Moraga-Gonzalez [12], Goyal and Joshi [13], and Westbrock [37]). Among the various models applied in R&D, the authors studied the incentives for companies to cooperate in R&D and the potential consequences for other economic factors. The common literature emphasizes the role of market structure or the degree of competition determined by the type of production in enhancing the contribution of collaborators. They have found that R&D investments increase as the degree decreases, and cooperation in a low competitive market always improves R&D spending. Also, the studies agreed on the positive principle of the gains that result from the cooperation of companies in R&D.

In addition, theoretical studies have examined the factors arising from R&D results such as uncertainty on the R&D results, imitation and spillover of the knowledge (e.g., Arrow [2], Belderbos *et al*. [3], Levine Prietula [20], and Liesch *et al*. [21]). These factors may have negative effects on investment incentives in R&D and other economic aspects. With regard to the spillover indirect effects, cooperation in R&D contributes to reducing this factor as well as reducing production costs (Silipo [31], and Tyler and Steensma [34]). Using the data from the US Department of Commerce on joint research ventures from 1985 to 1994, Röller *et al*. [29] found that the negative effects of the R&D spillover depend on industry and cooperation size. In our findings with the CATI database, we found that the R&D framework always grows despite the withdrawal of some companies. We also found that cooperation of companies involves different sectors which in turn represents the framework as overlapping structures. These findings reflect the importance of R&D cooperation in the development of companies.

The paper is organized as follows. Section 2 defines the data set and methodology for analyzing our results. Section 3 presents our results and discusses compatibility with theoretical results. Section 4 summarizes the results.

2. Data Description and Study Sample

2.1 Data Description

The work in this paper is based on the Cooperative Agreements and Technology Indicators (CATI) Database, developed by J. Hagedoorn and M. van Ekert at the University of Maastrich [16]. The data cover a number of types of cooperative agreements between different companies from different countries across different sectors for more than a century (1890-2006). The data also provide information about participating companies, industrial sectors and R&D agreements.

For participating companies, the data set provides the following information:

1. Names of companies and ownership
2. Year of establishment of companies
3. Fields of technology
4. Names and purposes of cooperation
5. Number of participants
6. Start and end cooperation

For cooperation agreements, they are classified into two main categories, each of which contains a set of agreement forms. In Appendix A, we provide further details on these agreements.

1. *Contractual*
   - *Joint Research Pact* (JRP)
   - *Joint Development Agreement* (JDA)
   - *R&D Contract* (RDC)
   - *Licensing* (L)
   - *Cross-Licensing* (XL)
   - *Standards* (S)
   - *Mutual Second Sourcing* (MSSA)
   - *Joint Ventures* (JV)
   - *Research Corporations* (RC)
   - *Minority Holding* (MH)
   - *Cross Holding* (CH)
2. *Joint Based*
   - *Joint Ventures* (JV)
   - *Research Corporation* (RC)
   - *Minority Holding* (MH)
   - *Cross Holding* (CH)

For industrial sectors, they are classified into four technological fields shown in Table 1.

Note that research projects involving single companies or universities are not supported by the data set.

2.2 Sample and Methodology

In this paper, we consider cooperation activity in the last two decades of the twentieth century, particularly from 1981 to 2000. We divide this period into four short epochs: 1981 to 1985; 1986 to 1990; 1991 to 1995; and 1996 to 2000. We cover all categories of R&D agreements in all four fields listed in Table 1 for all companies in the world without exception.

Our empirical technique is done by re-categorizing the data set in two stages. In the first stage, we improve the data to focus on the last two decades of the twentieth century and divide the period into four covenants. Second, in each epoch, we number companies from 1 to n where n is the total number of companies participated in R&D. Also, industrial sectors are numbered from 1 to 29 (total number of main sectors). Many of these sectors have sub-sectors and to avoid confusion, we combine sub-sectors and main sectors. Over the study period, companies

participated in R&D for many sectors and sub-sectors. The main sectors are 29 sectors where many of them contain sub-sectors. In this paper, we combine the sub-sectors with sectors and numbered them from 1 to 29. This method facilitates the process of differentiation between industrial sectors. In the second stage, the previous classifications and division are transferred to Microsoft Excel. In some cases, we use MATLAB to get results. In Appendix B, we provide more details about the actual work.

Table 1. The four technology fields as listed in the CATI database

Field 1	Biotechnology	Field 2	Information Technology
	Sectors		*Sectors*
	Agricultural biotechnology		Computers
	Environment		Industrial automation
	Pharmaceutical		Microelectronics
	Nutrition		Software
	Fine chemicals		Telecommunication
			Miscellaneous
Field 3	New Materials Technology	Field 4	Not Core Technology
	Sectors		*Sectors*
	Electro, magnetics & optics		Aircraft
	Technical ceramics		Automotive
	Powder metallics		Chemicals
	Fiber composites		Consumer electronics
	Technical plastics		Defense
	Metal alloys		Engineering & contracting
			Exploration, drilling & mining
			Food & beverage
			Heavy electrical equipment
			Instrumentation
			Medical technology
			Space technology

3. Statistics of R&D Partnerships

In this section we present the most important statistical features that describe the cooperation of domestic and international companies in R&D. Observations include the four technological fields and their sectors.

3.1 Participation of Companies in R&D

The starting point for our analysis of the database is the number of companies and agreements. During the period from 1981 to 2000, the participation of companies in R&D increased significantly as shown in Table 2. In the early to mid-1980s there were 2,362 companies cooperating in R&D across all technological fields. These companies are from 56 different countries where US companies accounted for 39.75% of all participating companies (see Table 3). In the next period from 1986 to 1990, the number of companies increased significantly about

double of companies in the first period. The number of countries involved in R&D increased to 63, and the United States remained primarily in terms of the number of participants. By the mid-1990s, the total number of participating companies was 5,872 due to companies that withdrew in the previous period, which is estimated at 11.49%. Also, the growth rate of companies fell compared to the previous period, falling by 17.44%. The number of countries involved in R&D remained as in the previous period, but the number of American companies participating in R&D increased from 39.90% to 46.19%. In the last period of our study, there was a proliferation of companies engaged in R&D, more than three times the number of companies in the first period. During this period, American companies that collaborated in R&D rose to 49.47%, the highest rate in all periods.

Table 2. Basic statistics for the participation of companies in R&D

Period	1981-1985	1886-1990	1991-1995	1996-2000
Number of companies	2,362	4,579	5,872	7,793
Number of new companies	-	2217	1819	1922
Growth rate of companies	-	48.42%	30.98%	24.66%
Number of withdrawing companies	0	526	1	-
Percentage of withdrawing companies	0	11.49%	0.02%	-
Number of R&D agreements	3,169	7,479	8,767	11,572
Average number of agreements per company	1.34	1.61	1.49	1.48
Growth rate of agreements	-	57.63%	14.69%	24.24%

The growth of R&D cooperation has been confirmed by a number of authors. Using CATI database, Silipo [31] found that for research joint ventures that participating companies increased significantly throughout the last three decades of the twentieth century. Also, he found that the cooperation is concentrated in the United States, Japan and Europe. Moreover, Hagedoorn and Schakenraad [15] concluded that the cooperation in the information and communication technology industries in the 1980s was based on seven companies, mostly from the United States and Japan. Furthermore, this conclusion was confirmed by Tomasello *et al*. [33] who used the SDC Platinum database to study collaboration of companies in R&D from 1986 to 2009.

3.2 Descriptive Statistics of Industrial Sectors

Table 4 displays ratios of participation in the four fields: biotechnology, information technology, new materials technology and not core technology[1]. It can be observed that not core technology was the most common field in all study periods with nearly half of existing companies. The information technology received the same attention throughout the study period, but it ranked second. In the early to mid-1980s, the percentages of companies in the two fields of the total number of companies were 45.60% and 40.01%, respectively. However, these percentages declined slightly in the second period from 1986 to 1990. During the following periods, the ratio of companies in the not core technology and information technology increased again, reaching 45.09% and 42.67%, respectively.

[1]Many companies participate in R&D for more than one field and the percentages shown in the table is over total companies in each period.

Table 3. The ten most cooperative countries in R&D

1981-1985		1886-1990	
Country	Participation %	Country	Participation %
USA	39.75	USA	39.90
Japan	12.26	Japan	10.30
UK	9.12	UK	8.49
Germany	5.52	Netherlands	6.94
Netherlands	5.18	Germany	5.93
France	4.92	France	4.27
Italy	4.58	Italy	3.57
Sweden	2.67	Sweden	2.01
Canada	1.82	Canada	1.66
Switzerland	1.32	Belgium	1.55
1991-1995		1996-2000	
Country	Participation %	Country	Participation %
USA	46.19	USA	49.47
UK	8.07	UK	7.62
Japan	7.84	Japan	6.77
Germany	5.68	Germany	6.05
Netherlands	5.42	Netherlands	4.41
France	4.13	France	3.93
Italy	2.93	Italy	2.48
Canada	1.74	Canada	2.29
Sweden	1.74	Sweden	1.62
Soviet Union	1.45	Peoples Republic of China	1.39

Table 4. Cooperation of companies in R&D in the four fields

Period / Fields	1981-1985	1886-1990	1991-1995	1996-2000
Biotechnology				
Percentage of participation	17.74	18.32	21.92	22.89
Number of R&D agreements	11.17	24.81	27.38	36.64
Information Technology				
Percentage of participation	40.01	39.40	40.34	42.67
Number of R&D agreements	11.93	26.64	27.34	34.08
New Materials Technology				
Percentage of participation	17.32	19.48	16.62	14.95
Number of R&D agreements	11.60	29.22	28.17	31.01
Not Core Technology				
Percentage of participation	45.60	44.31	44.65	45.09
Number of R&D agreements	11.34	27.15	28.06	33.44

Table 5. Cooperation of companies in R&D in the not core technology field

Sectors \ Period	1981-1985	1886-1990	1991-1995	1996-2000
Aircraft				
Percentage of participation	1.02	2.03	3.61	3.66
Percentage of R&D agreements	1.37	1.56	3.19	3.55
Automotive				
Percentage of participation	25.32	43.22	34.62	28.54
Percentage of R&D agreements	56.48	56.83	50.58	46.02
Chemicals				
Percentage of participation	7.32	13.08	14.34	13.91
Percentage of R&D agreements	12.81	12.03	16.10	17.48
Consumer Electronics				
Percentage of participation	1.82	2.93	2.69	2.90
Percentage of R&D agreements	2.50	2.23	2.40	2.96
Defense				
Percentage of participation	2.24	4.30	4.80	4.65
Percentage of R&D agreements	3.34	4.53	5.59	6.01
Engineering & Contracting				
Percentage of participation	5.17	9.85	9.21	8.60
Percentage of R&D agreements	10.60	11.03	10.81	10.45
Exploration, Drilling& Mining				
Percentage of participation	0.97	1.81	1.19	0.98
Percentage of R&D agreements	1.28	0.96	0.73	0.67
Food & Beverage				
Percentage of participation	0.85	2.80	3.03	2.44
Percentage of R&D agreements	1.03	1.56	2.02	1.80
Heavy Electrical Equipment				
Percentage of participation	3.39	5.53	4.09	3.81
Percentage of R&D agreements	5.69	4.82	3.75	3.81
Instrumentation				
Percentage of participation	2.20	3.80	3.05	3.76
Percentage of R&D agreements	3.09	2.28	2.10	2.80
Medical Technology				
Percentage of participation	0.67	1.55	1.55	3.0
Percentage of R&D agreements	0.83	0.92	1.11	2.50
Space Technology				
Percentage of participation	0.68	1.92	2.11	2.35
Percentage of R&D agreements	0.98	1.25	1.61	1.96

With regard to the number of R&D agreements, we found that the increase was significantly high during the last period of our study from 1996 to 2000. Also, the field of information technology had the largest number of agreements in the first period, but this changed over the following two periods, as new materials technology received the highest degree of attention. During the last period, the majority of R&D agreements were in biotechnology with ratio 36.64% out of all agreements made in that period. The field of information technology ranked second in terms of the number of agreements with 34.08%.

Table 5 provides more details on the not core technology field, which is the largest field in terms of number of collaborating companies. As shown in the table, the highest level of cooperation was in the automotive and chemical sectors. From 1981 to 1986, the proportion of companies in these sectors was 25.32% and 7.32% of total companies, respectively. Companies involved in these sectors accounted for 56.48% and 12.81% of total agreements. In the following period, the proportion of companies increased almost double (43.22% and 13.08%); while the change in the number of agreements was slight. In the last decade of the twentieth century, the proportion of companies and R&D agreements in the automotive sector declined, but it is still higher than other sectors. For the chemicals sector, the proportion of companies rose slightly and then fell to 13.91% of the total companies in that period. Similar patterns can be observed in terms of the agreements in this sector. On the other hand, the sectors of exploration and drilling, medical technology and space technology were characterized by a low rate of cooperation, with the proportion of companies and agreement in these sectors in all periods not exceeding 3%.

Table 6 shows the cooperation between companies in the sectors of the information technology field. It can be noted that the telecommunications sector has captured the largest proportion of companies cooperating in this field. This sector started with 48.14% of the total number of companies in the information technology field and made 62.39% of R&D agreements. In the following period, this sector ranked first in terms of rates of participation and agreements. During those two periods, the industrial automation sector ranked second in terms of participating companies by 19.82% and 16.25%, respectively. During the 1990s, the rate of participating companies and R&D agreements fell in the telecommunications sector, but remained high compared to other sectors in the information technology field. Also, the software sector jumped to second place in both the number of participants and agreements in this field. On the other hand, cooperation in computers and miscellaneous sectors was slight during the period of study, where the proportion of companies did not exceed 10% and 7%, respectively.

Tables C1 and C2 in Appendix C show the cooperation in the sectors of the biotechnology and new materials technology, respectively. In the biotechnology field, cooperation was significant in the agricultural biotechnology and pharmaceutical sectors, while in the environment and nutrition sectors it was very small. For new materials technology field, most cooperation was in the sector of electro, magnet and optics. This was followed by sectors of technical ceramics and plastics. In contrast, cooperation in the powder metallics sector was small, especially during the 1990s with a collaboration rate of less than 7%.

Table 6. Cooperation of companies in R&D in the information technology field

Sectors / Period	1981-1985	1886-1990	1991-1995	1996-2000
Computers				
Percentage of participation	7.03	7.96	9.22	8.70
Percentage of R&D agreements	5.81	6.51	8.26	8.08
Industrial automation				
Percentage of participation	19.82	16.25	16.03	16.64
Percentage of R&D agreements	12.68	9.75	9.75	10.77
Microelectronics				
Percentage of participation	10.60	9.05	9.92	12.69
Percentage of R&D agreements	11.13	9.99	11.78	13.98
Software				
Percentage of participation	9.73	14.40	18.92	20.50
Percentage of R&D agreements	5.58	10.20	16.13	18.31
Telecommunication				
Percentage of participation	48.14	46.02	41.17	36.05
Percentage of R&D agreements	62.39	60.81	51.85	46.14
Miscellaneous				
Percentage of participation	4.69	6.31	4.73	5.41
Percentage of R&D agreements	2.40	2.73	2.23	2.72

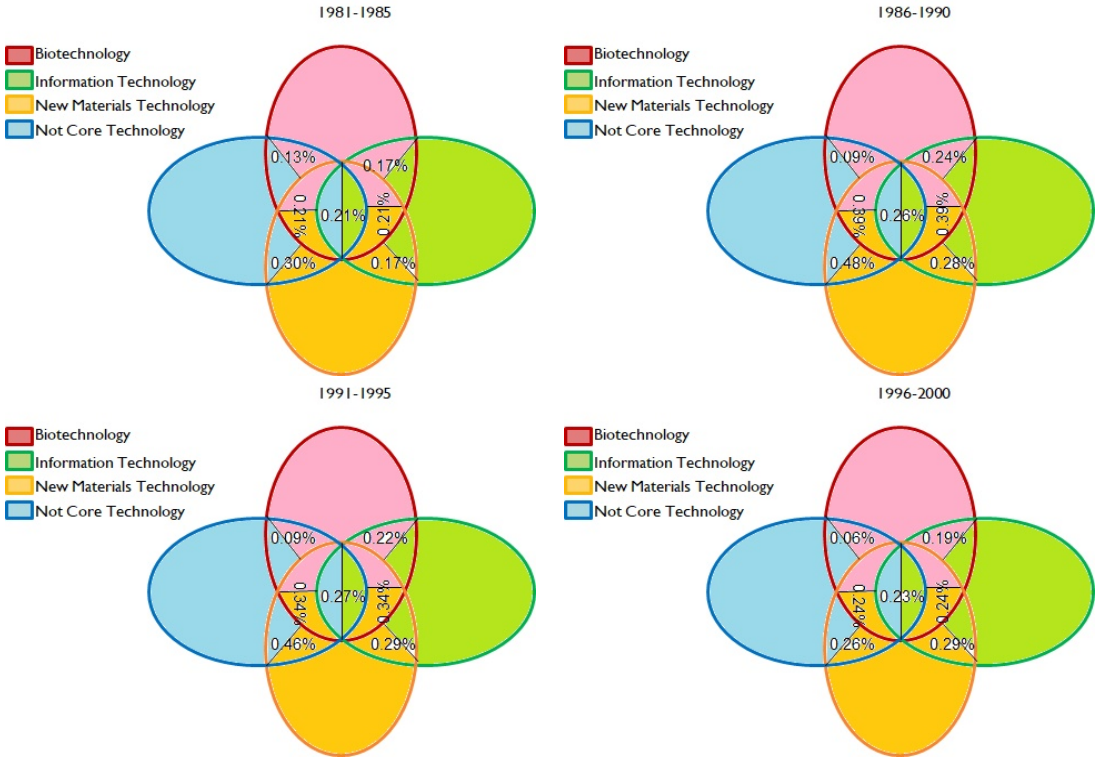

Figure 1. Companies' participation in R&D for more than a technological field

Figure 1 shows the percentage of intersection between the four technological fields out of the total number of companies in each period. It seems that the commonality between new materials technology and not core technology in terms of participating companies was high compared to relationships among other technological fields. There have also been high commonalities between new materials technology and both biotechnology and information technology. This shows that a high proportion of participants in the new materials technology have participated in other technology fields. The most prominent example of the participation of companies in various technological fields is Mitsubishi. From 1981 to 1985, this company cooperated in R&D with many other companies in four technology fields. This company continued to cooperate in the four technology fields during the following periods. Also, other companies have cooperated in the four fields such as Mitsui, Nippon Steel and Sumitomo from 1991 to 1995. Table 7 provides examples of companies engaged in R&D for more than one technology field.

Table 7. Examples of companies involved in R&D for more than one technological field

Period	Example	Number of technology fields	Period	Example	Number of technology fields
	Mitsubishi	4		Mitsubishi	4
	Siemens A.G.	3		Nippon Steel	4
1981-1985	Toshiba	3	1986-1990	Sumitomo	4
	Sumitomo	3		Siemens A.G.	3
	Mitel	2		General Electric Co.	3
	Mitsubishi	4		Mitsubishi	4
	Mitsui	4		Mitsui	4
1991-1995	Nippon Steel	4	1996-1920	Nippon Steel	4
	Sumitomo	4		Sumitomo	4
	European Space Agency	3		Kodak	3

Table 8 provides further analysis for those companies that have concluded many R&D agreements[2]. The table shows the maximum percentages of R&D agreements of the number of agreements in all sectors together. It can be observed that Mitsubishi, Philips, and IBM were the most cooperative in the entire study period. Interestingly, IBM was more involved in R&D, but did not enter all technological fields. A study by Hernán *et al*. [17] found that the increasing cooperation of some companies in R&D may be due to past successes and experience gained. Also, the increasing cooperation of some companies in R&D is due to previous successes and experiences and their absorptive capacity (Miotti and Sachwald [23]).

[2]Some companies are encoded as mentioned in the data set. Philips refers to Philips Gloeilampenfabrieken N.V. and Hitachi refers to Hitachi Ltd.

Table 8. Maximum percentages of R&D agreements in all sectors together

Period	Company	Number of Agreements	Period	Company	Number of Agreements
	Mitsubishi	1.63		Philips	1.39
	Philips	1.41		Mitsubishi	1.24
1981-1985	Olivetti	1.33	1986-1990	IBM	1.20
	Hitachi	1.13		Siemens	1.09
	Siemens	1.06		Olivetti	0.92
	IBM	1.31		IBM	1.30
	Mitsubishi	1.03		Mitsubishi	0.89
1991-1995	Philips	0.99	1996-2000	Siemens	0.88
	SIEMENS	0.92		Philips	0.87
	Hewlett-Packard Co.	0.79		Hewlett-Packard Co.	0.80

3.3 Descriptive Statistics of R&D Agreements

Table 9 compares the use of R&D forms on page 1892 during the study period.[3] Between 1981 and 1985, most companies chose the licensing form for R&D cooperation by 24.78%. The joint development agreements ranked second with 24.35%, followed by joint ventures (21.65%) and minority holding (18.05%). By contrast, the other forms such as standards, research corporation and cross holding were the lowest forms of R&D agreements among companies. In the second period from 1986 to 1990, the use of the licensing form decreased compared to the joint development agreements, which ranked first with 30.95% of R&D agreements. The forms of mutual second sourcing and cross holding were the least used during that period, where the ratio was less than 1%.

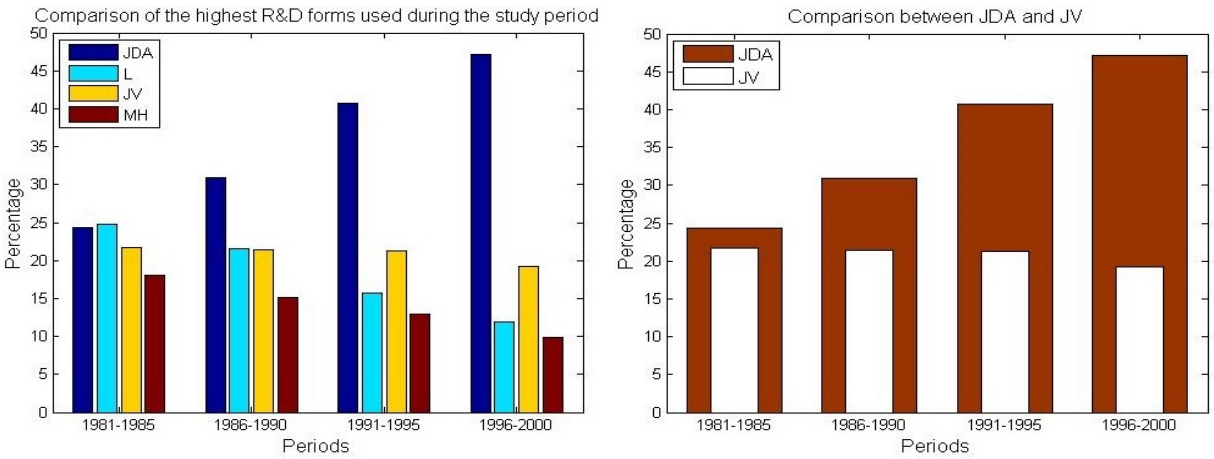

Figure 2. Percentage of R&D forms used in the last two decades of the twentieth century. The figure on the right compares the highest R&D forms used during the study period, while the figure on the left side compares the joint development agreements and joint ventures

[3]Some alliances carried more than one form of R&D agreements. For this reason, the sum of the agreements in each period may exceed the total number of conventions contained in Table 2.

Table 9. Cooperation of companies in different R&D agreements

Period	JRP	JDA	RDC	L	XL	S	MSSA	JV	RC	MH	CH
1981-1985	2.06	24.35	4.80	24.78	1.54	0.81	0.90	21.65	0.90	18.05	0.17
1986-1990	1.97	30.95	4.73	21.54	1.26	1.03	0.59	21.41	1.10	15.17	0.25
1991-1995	1.75	40.75	3.10	15.67	2.12	0.81	0.44	21.23	0.96	12.94	0.23
1996-2000	1.60	47.16	5.95	11.90	2.20	0.67	0.33	19.18	0.91	9.92	0.18

In the early to mid-1990s, 40.75% of the 8,767 agreements were the joint development agreements and this ratio is high compared to other forms of R&D agreements. During that period, the joint ventures ranked the second with 21.23%. The other forms like licensing and minority holding decreased in that period to 15.67% and 12.94%, respectively. During the period from 1996 to 2000, the joint development agreement continued to rise to nearly half the total number of agreements; while the joint ventures dropped slightly to 19.18%. Figure 2 compares the highest R&D forms used during the study period.

3.4 Experimental vs. Theoretical Results

In this section, we examine the compatibility of our empirical results with the theoretical results. The R&D cooperation is widely discussed in the theoretical literature with specific attention to the impact of cooperation on other economic outcomes. D'Aspremont and Jacquemin [7] compared R&D cooperation and research joint venture (RJV) activity within the homogeneous goods of two companies competing by setting production quantities. Their model has become a base of many investigations that interest the effect of cooperation on R&D investments, outputs and profits. Kamien *et al*. [18], and Suzumura [32] studied cooperation in R&D for an arbitrary number of companies with differentiated goods. Ziss [42] assumed that companies competed in the market by determining their quantities and prices[4]. Goyal and Moraga-Gonzalez [12] and their followers extended the original model by D'Aspremont and Jacquemin by introducing the concept of the network[5]. Their Investigations focused primarily on the impact of conventions on outcomes and on the identification of structures in which individuals and society enjoyed high benefits.

The common literature in all previous papers is that there is a possibility that companies benefit from the knowledge generated by other companies. This may have negative effects on companies' spending on R&D and profits. In addition to the effects caused by uncertainty on the results of R&D and the imitation of knowledge (e.g., Arrow [2], Belderbos *et al*. [3], Levine and Prietula [20], Liesch *et al*. [21], and Zhang and Yang [38]). With regard to the R&D spillover, inter-firm cooperation should be encouraged (Conti and Marini [5], Goyal and Moraga-Gonzalez [12], Goyal and Joshi [13], and Silipo [31]). This conclusion is supported by our findings in this paper, as the structure of R&D cooperation expands over time.

[4]Recently, many researchers have extended the original work by D'Aspremont and Jacquemin in many directions (e.g., Kobayashi [19], Zhou *et al*. [40], and Zhou *et al*. [41]).

[5]The importance of the network concept is reflected in R&D cooperation by linking research and development cooperation with network literature. The latter is a tool for understanding change in investments while changing the number of R&D agreements in relation to the type and intensity of competition. As well as the importance of networks in identifying profitable structures for all companies. There are several studies that have used the network framework to study the impact of R&D cooperation on economic outcomes (e.g., Alghamdi [1], Deroian [8], and Westbrock [37]).

Moreover, theoretical conclusions emphasize the importance of overlapping between companies that produce different products for higher profits (e.g. Goyal and Moraga-Gonzalez [12], Grandjean and Vergote [14], Röller *et al*. [29], and Zhang and Zhang [39]). Hernán *et al*. [17] also found that such overlapping structures are useful for companies in identifying the right partners for successful collaboration. Cowan and Jonard [6] carried out numerical simulations regarding to knowledge diffusion and the innovation. The results suggest that dense structures encourage the spread of knowledge[6]. Our findings pointed to these results, where it was noted that many collaborations were characterized by diversity. We have found that many companies prefer to develop R&D agreements to serve more than one sector, for example, Mitsubishi, Mitsui, Nippon Steel and Sumitomo. Also, our findings confirm the importance of the diversity of the cooperation. We have found that many companies prefer to develop R&D agreements to serve more than one sector, for example, Mitsubishi, Mitsui, Nippon Steel and Sumitomo. These companies cooperated in the four technological fields during the study period. Also, other companies such as Bull and Eastman Kodak have collaborated in at least two technological fields.

4. Conclusion

This paper contributed to the experimental work of R&D participation of companies around the world by studying the structure of cooperation and its development over time. We used the CATI Database and considered all types of R&D agreements for both domestic and international contracts during the last two decades of the twentieth century.

The substantial growth in R&D cooperation is a key feature of the four technological fields. The most active companies played an important role in this growth, where the focus of cooperation was in three countries: the United States, Japan and the United Kingdom. Among the technological fields, not core technology and information technology were the most participatory fields during the study period. In the not core technology field, the majority of companies were in the automotive and chemical sectors while in the information technology field, the majority were in the telecommunications sector. The study also focused on distinguishing between the forms of R&D agreements. Among the various forms, we found that joint development agreements and joint ventures were more common than others.

In addition, the paper also addressed the consistency of our empirical findings with the theoretical results. In theory, first, the R&D cooperation leads to success in the economic outcomes of companies, especially when the cooperation involves diverse companies. Second, the cooperation contributes to reducing the R&D spillover factor, which is a negative factor on the economic component of companies, in particular when they are in a competitive market. Our analysis confirms these results as we found that R&D partnerships are intensive and that many agreements serve more than one industrial sector. In particular, very active companies such as Mitsubishi and Philips participated in R&D for at least three fields of technology and played an essential role in growing the R&D cooperation system through increasing their agreements.

[6]There are other studies concluded the same result such as Fleming *et al*. [11], and Morone and Taylor [24]. More recently, these works have been followed by many authors (e.g., Mueller *et al*. [25], Schlaile *et al*. [30], and Wang *et al*. [36])

Appendices

Appendix A: Classification of R&D Agreements

1. *Contractual*
   (a) *Joint Research Pact* (JRP): Agents joint their research projects and share resources.
   (b) *Joint Development Agreement* (JDA): Agents work together on new technology or products.
   (c) *R&D Contract* (RDC): One agent achieves R&D projects and other finance.
   (d) *Licensing* (L): One company having proprietary rights (patents) or know-how gives another company the right of use in return for payments.
   (e) *Cross-Licensing* (XL): Covering arrangements regulating license-swapping.
   (f) *Standards* (S): Collaboration to set world-wide or regional industrial standards.
   (g) *Mutual Second Sourcing* (MSSA): Companies share technology so they can produce each other goods.
2. *Joint Based*
   (a) *Joint Ventures* (JV): At least two agents combine their economic interests in a separate agent and share profits.
   (b) *Research Corporation* (RC): Agents joint R&D ventures with specific research programs.
   (c) *Minority Holding* (MH): One company acquires a minor (less than 50%) interest in another company.
   (d) *Cross Holding* (CH): Two companies take a minority interest in each other at the same time.

Appendix B: Actual Work to Obtain the Results

The actual work of analyzing the data set was done in two phases.

First Stage (Microsoft Excel)

1. *Divide the data into six epochs*: The study in this paper covered the period from 1981 to 2000. This period is divided into four short epochs: 1981-1985, 1986-990, 1991-1995 and 1996-2000. The decision to divide the last two decades of the twentieth century in these four periods depends on the number of companies engaged in R&D, which has increased significantly over time. The collaboration information in these epochs is arranged in four spreadsheets, each of which represents a single period.
2. *Codify companies*: Each company is assigned a digit from 1 to n where n is the total number of companies participating in R&D in the time period of the data set.
3. *Codify sectors*: The industrial sectors are divided into four general fields as listed in Table 1. In our work, we have assigned a number to each sector in a manner that will continue in all periods.

Second Stage (MATLAB)

In this stage, we transfer the cooperation information given the first stage into MATLAB by using 'xlsread' command. Then, we built codes to obtain the results.

Appendix C: Biotechnology and New Materials Technology Fields

Table C1. Cooperation of companies in R&D in the biotechnology field

Sectors \ Period	1981-1985	1886-1990	1991-1995	1996-2000
Agricultural biotechnology				
Percentage of participation	51.73	49.63	44.62	39.66
Percentage of R&D agreements	64.80	63.54	53.47	44.41
Environment				
Percentage of participation	4.81	6.49	6.35	5.13
Percentage of R&D agreements	1.96	2.22	2.36	1.87
Pharmaceutical				
Percentage of participation	26.17	25.21	34.87	42.45
Percentage of R&D agreements	24.92	25.62	37.20	47.60
Nutrition				
Percentage of participation	7.16	6.18	4.28	3.85
Percentage of R&D agreements	3.49	2.64	1.94	1.69
Fine chemicals				
Percentage of participation	10.12	12.48	9.89	8.91
Percentage of R&D agreements	4.85	5.97	5.03	4.43

Table C2. Cooperation of companies in R&D in the new materials technology field

Sectors \ Period	1981-1985	1886-1990	1991-1995	1996-2000
Electro, Magnetics & Optics				
Percentage of participation	46.21	46.14	43.77	45.53
Percentage of R&D agreements	58.20	57.84	53.28	54.02
Technical ceramics				
Percentage of participation	16.16	17.29	16.09	14.75
Percentage of R&D agreements	13.16	13.95	12.62	11.52
Powder metallics				
Percentage of participation	7.46	6.57	6.54	5.94
Percentage of R&D agreements	4.95	4.30	4.33	4.05
Fiber composites				
Percentage of participation	10.17	9.09	9.35	9.35
Percentage of R&D agreements	9.29	7.81	8.48	8.34
Technical plastics				
Percentage of participation	13.45	13.03	16.70	16.87
Percentage of R&D agreements	10.53	10.94	15.81	16.44
Metal alloys				
Percentage of participation	6.55	7.88	7.56	7.56
Percentage of R&D agreements	3.87	5.16	5.48	5.62

Acknowledgment

The author extends his appreciation to the Deanship of Scientific Research at King Saud University for funding this work through the Research Project No R5-16-03-11.

Availability of supporting data

The data that support the findings of this study are available from the corresponding author upon reasonable request (data usage license provided).

Competing Interests

The author declares that he has no competing interests.

Authors' Contributions

The author wrote, read and approved the final manuscript.

References

[1] M. Alghamdi, Economic returns in forming stable R&D networks, *SpringerPlus* **5** (2016), Article number: 1570, DOI: 10.1186/s40064-016-3260-8.

[2] K. J. Arrow, Classificatory notes on the production and transmission of technological knowledge, *The American Economic Review* **59**(2) (1969), 29 – 35, URL: https://www.jstor.org/stable/1823650.

[3] R. Belderbos, M. Carree and B. Lokshin, Cooperative R&D and firm performance, *Research Policy* **33**(10) (2004), 1477 – 1492, DOI: 10.1016/j.respol.2004.07.003.

[4] Y. Caloghirou, S. Ioannides and N. S. Vonortas, Research joint ventures, *Journal of Economic Surveys* **17**(4) (2003), 541 – 570, DOI: 10.1111/1467-6419.00204.

[5] C. Conti and M. A. Marini, Are you the right partner? R&D agreement as a screening device, *Economics of Innovation and New Technology* **28**(3) (2019), 243 – 264, DOI: 10.1080/10438599.2018.1466471.

[6] R. Cowan and N. Jonard, The dynamics of collective invention, *Journal of Economic Behavior & Organization* **52**(4) (2003), 513 – 532, DOI: 10.1016/S0167-2681(03)00091-X.

[7] C. D'Aspremont and A. Jacquemin, Cooperative and noncooperative R&D in duopoly with spillovers, *The American Economic Review* **78** (1988), 1133 – 1137, URL: https://www.jstor.org/stable/1807173.

[8] F. Deroian, Dissemination of spillovers in cost-reducing alliances, *Research in Economics* **62**(1) (2008), 34 – 44, DOI: 10.1016/j.rie.2007.12.004.

[9] M. A. Desai, C. F. Foley and J. R. Hines Jr., The costs of shared ownership: Evidence from international joint ventures, *Journal of Financial Economics* **73**(2) (2004), 323 – 374, DOI: 10.1016/j.jfineco.2003.07.001.

[10] E. Eerola and N. Määttänen, Strategic alliances, joint investments, and market structure, *International Journal of Industrial Organization* **22**(2) (2004), 241 – 251, DOI: 10.1016/j.ijindorg.2003.09.001.

[11] L. Fleming, C. King, III and A. I. Juda, Small worlds and regional innovation, *Organization Science* **18**(6) (2007), 885 – 1027, DOI: 10.1287/orsc.1070.0289.

[12] S. Goyal and J. Moraga-Gonzalez, R&D networks, *RAND Journal of Economics* **32**(4) (2001), 686 – 707, DOI: 10.2307/2696388.

[13] S. Goyal and S. Joshi, Networks of collaboration in oligopoly, *Games and Economic Behavior* **43**(1) (2003), 57 – 85, DOI: 10.1016/S0899-8256(02)00562-6.

[14] G. Grandjean and W. Vergote, Network formation among rivals, USL-B-Université Saint-Louis, Mimeo, 40 pages (2015), URL: https://cerec.be/wp-content/uploads/2018/01/network-formation-among-rivals_feb13.pdf.

[15] J. Hagedoorn and J. Schakenraad, The effect of strategic technology alliances on company performance, *Strategic Management Journal* **15**(4) (1994), 291 – 309, DOI: 10.1002/smj.4250150404.

[16] J. Hagedoorn and M. van Ekert, *The Cooperative Agreements and Technology Indicators Database*, MERIT Maastricht University, Maastricht (2002).

[17] R. Hernán, P. L. Marín and G. Siotis, An empirical evaluation of the determinants of research joint venture formation, *The Journal of Industrial Economics* **51**(1) (2003), 75 – 89, DOI: 10.1111/1467-6451.00192.

[18] M. I. Kamien, E. Muller and I. Zang, Research joint ventures and R&D cartels, *American Economic Review* **82**(5) (1992), 1293 – 1306.

[19] S. Kobayashi, On a dynamic model of cooperative and noncooperative R and D in oligopoly with spillovers, *Dynamic Games and Applications* **5**(4) (2015), 599 – 619, DOI: 10.1007/s13235-014-0117-z.

[20] S. S. Levine and M. J. Prietula, How knowledge transfer impacts performance: a multilevel model of benefits and liabilities, *Organization Science* **23**(6) (2012), 1523 – 1783, DOI: 10.1287/orsc.1110.0697.

[21] P. W. Liesch, L. S. Welch and P. J. Buckley, Risk and uncertainty in internationalisation and international entrepreneurship studies, in: *The Multinational Enterprise and the Emergence of the Global Factory*, Palgrave Macmillan, London (2014), DOI: 10.1057/9781137402387_3.

[22] A. López, Determinants of R&D cooperation: Evidence from Spanish manufacturing firms, *International Journal of Industrial Organization* **26**(1) (2008), 113 – 136, DOI: 10.1016/j.ijindorg.2006.09.006.

[23] L. Miotti and F. Sachwald, Co-operative R&D: Why and with whom?: An integrated framework of analysis, *Research Policy* **32**(8) (2003), 1481 – 1499, DOI: 10.1016/S0048-7333(02)00159-2.

[24] P. Morone and R. Taylor, Knowledge diffusion dynamics and network properties of face-to-face interactions, *Journal of Evolutionary Economics* **14**(3) (2004), 327 – 351, DOI: 10.1007/s00191-004-0211-2.

[25] M. Mueller, K. Bogner, T. Buchmann and M. Kudic, The effect of structural disparities on knowledge diffusion in networks: An agent-based simulation model, *Journal of Economic Interaction and Coordination* **12**(3) (2017), 613 – 634, DOI: 10.1007/s11403-016-0178-8.

[26] R. Narula, *R&D Collaboration by SMEs: Some Analytical Issues and Evidence*, in: *Cooperative Strategies and Alliances*, F. Contractor and A. Lorange (editors), Pergamon Press, Oxford (2002).

[27] B. Nooteboom, Innovation and inter-firm linkages: New implications for policy, *Research Policy* **28**(8) (1999), 793 – 805, DOI: 10.1016/S0048-7333(99)00022-0.

[28] E. Petrakis and N. Tsakas, The effect of entry on R&D networks, *The RAND Journal of Economics* **49**(3) (2018), 706 – 750, DOI: 10.1111/1756-2171.12250.

[29] L.-H. Röller, R. Siebert and M. Tombak, *Why Firms Form Research Joint Ventures: Theory and Evidence*, CEPR Discussion Papers 1654, C.E.P.R. Discussion Papers (1997).

[30] M. P. Schlaile, Jo. Zeman and M. Mueller, It's a match! Simulating compatibility-based learning in a network of networks, in: *Memetics and Evolutionary Economics. Economic Complexity and Evolution*, M. P. Schlaile (editor), Springer, Cham. (2021), DOI: 10.1007/978-3-030-59955-3_5.

[31] D. B. Silipo, Incentives and forms of cooperation in research and development, *Research in Economics* **62**(2) (2008), 101 – 119, DOI: 10.1016/j.rie.2008.04.003.

[32] K. Suzumura, Cooperative and noncooperative R&D in an oligopoly with spillovers, *The American Economic Review* **82**(3) (1992), 1307 – 1320, URL: https://www.jstor.org/stable/2117480.

[33] M. V. Tomasello, M. Napoletano, A. Garas and F. Schweitzer, The rise and fall of R&D networks, *Industrial and Corporate Change* **26**(4) (2017), 617 – 646, DOI: 10.1093/icc/dtw041.

[34] B. B. Tyler and H. K. Steensma, Evaluating technological collaborative opportunities: A cognitive modeling perspective, *Strategic Management Journal* **16** (S1), 43 – 70, DOI: 10.1002/smj.4250160917.

[35] N. S. Vonortas, Multimarket contact and inter-firm cooperation in R&D, in: *Capitalism and Democracy in the 21st Century*, D. C. Mueller and D. C. Cantner (editors), Physica, Heidelberg (2001), DOI: 10.1007/978-3-662-11287-8_13.

[36] H. Wang, J. Wang, L. Ding and W. Wei, Knowledge transmission model with consideration of self-learning mechanism in complex networks, *Applied Mathematics and Computation* **304** (2017), 83 – 92, DOI: 10.1016/j.amc.2017.01.020.

[37] B. Westbrock, Natural concentration in industrial research collaboration, *The RAND Journal of Economics* **41**(2) (2010), 351 – 371, DOI: 10.1111/j.1756-2171.2010.00103.x.

[38] Y. Zhang and N. Yang, Development of a mitigation strategy against the cascading propagation of risk in R&D network, *Safety Science* **68** (2014), 161 – 168, DOI: 10.1016/j.ssci.2014.04.006.

[39] A. Zhang and Y. Zhang, Rivalry between strategic alliances, *International Journal of Industrial Organization* **24**(2) (2006), 287 – 301, DOI: 10.1016/j.ijindorg.2005.04.005.

[40] Q. Zhou, T. Li, W. Yang and L. Wang, Investment decision model of industrial technologies and innovation strategic alliance regarding conflict based on plant growth simulation algorithm, *Applied Mathematics & Information Sciences* **8**(3) (2014), 1369 – 1375, DOI: 10.12785/amis/080354.

[41] J. Zhou, W. Zhou, T. Chu, Y.-X. Chang and M.-J. Huang, Bifurcation, intermittent chaos and multi-stability in a two-stage Cournot game with R&D spillover and product differentiation, *Applied Mathematics and Computation* **341** (2019), 358 – 378, DOI: 10.1016/j.amc.2018.09.004.

[42] S. Ziss, Strategic R&D with spillovers, collusion and welfare, *The Journal of Industrial Economics* **42**(4) (1994), 375 – 393, DOI: 10.2307/2950444.