University-Industry Collaboration Networks for the Creation of Innovation: A Comparative Analysis of the Development of Lead-Free Solders in Japan, Europe and the United States

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Abstract

This study examined how collaboration networks are formed among university, industry and the public sector and work for the creation of innovation. The focus of this study is placed on the development of lead-free solders in the electric and electronic industry in Japan, Europe, and the United States. The structure of innovation networks on lead-free solders is analyzed with quantitative methods of social network analysis, based on data on the membership of research and development projects and scientific papers. While initiatives to regulate the use of lead for soldering were made earlier in the United States, development and adoption of lead-free solders progressed significantly in Japan through the formation of research and development networks. This case suggests that university could play a crucial role in establishing innovation networks among relevant actors in the private as well as public sectors. To implement an effective transition to lead-free solders, cooperation and coordination was indispensable among relevant actors, including those working on chip implementation, solders, manufacturing equipment, parts, devices, print boards, and measurement instruments. In the absence of a domestic institutional framework for regulating the use of lead, it was crucial that university researchers, working from a relatively neutral position, took the initiative in creating collaboration networks for the formulation of industry-wide roadmaps for technological development and implementation, evaluation and standardization of various specifications, and accumulation of scientific and technological knowledge.

Keywords: *university-industry collaboration, lead-free solder, innovation, network, institution, environmental regulation, United States, Europe, Japan, electronic industry*

1. Introduction

In the era of knowledge-based economies, rapid knowledge creation and easy access to knowledge bases are considered to make a key contribution to innovation (Foray, 2004). As the commercialization of knowledge has assumed greater importance in economic growth, collaboration across organizational boundaries has become more commonplace. In fields where scientific or technological progress is developing rapidly and the sources of knowledge are widely distributed, no single organization has all the necessary skills to stay on top of all areas of progress and bring forth significant innovation (Powell and Grodal, 2005). Many of recent studies suggest the crucial role of inter-organizational networks in influencing the change and direction of technological development. Reviewing the past findings of empirical research on the role of external sources of scientific, technical and market information in innovation, Freeman pointed out the vital importance of external information networks and of collaboration with users during the development of new products and processes (Freeman, 1991). It is argued that dense ties between partners in technology collaboration networks foster information diffusion and knowledge exchange, enhancing the technological performance and collaborating opportunities of the partners (Ahuja, 2000; Stuart, 1998; Uzzi, 1997). Other innovation studies explain the benefits of inter-organizational relationships in terms of mutual and interactive learning through networks (Gulati, 1999; Powell, Koput, and Smith-Doerr, 1996).

Traditionally assumed to be responsible for producing and disseminating knowledge, universities are now expected to be an essential institutional actor in pursuing economic and social goals, and governments in industrialized as well as developing countries increasingly regard universities as instruments for promoting innovation, rather than ivory towers devoted to the pursuit of knowledge for its own sake (Mowery, Nelson, Sampat, and Ziedonis, 2004). For this purpose, various attempts have been initiated in many parts of the world to foster the relationship of university-industry collaboration. In Japan, for example, the number of joint research projects between universities and companies in the private sector has continued to rise since the start of data collection in 1983, according to a study conducted by the National Institute of Science and Technology Policy (NISTEP) (Nakayama, Hosono, Fukugawa, and Kondo, 2005). Particularly since the 1990s, when laws and policies aimed at promoting university-industry collaboration, notably the Science and Technology Basic Law in 1995, the First Science and Technology Basic Plan in 1996, and the Law for Promoting Technology Transfer from University in 1998, were enacted or implemented, university-industry collaboration has been increasingly intensified across Japan. It is reported by the Ministry of Education, Culture, Sports, Science and Technology (2005) that as the number of joint research contracts jumped from 1,139 in 1991 to 9,378 in 2004, the amount of research funding provided by contract partners also increased from less than 4 billion Japanese yen in 1995 to 20 billion yen in 2004. Patent licensing via technology liaison offices (TLOs) of universities has grown rapidly since the first case was reported in 1998, reaching to the level of 223 cases in 2004.

University-industry collaboration produce outputs in different forms, including, among others, scientific and technological information and knowledge, equipment and instrumentation, prototypes for new products and processes, skills and human capital, capacity for scientific and technological problem-solving, and networks of scientists and technologists (Mowery and Sampat, 2005; Salter, D'Este, Pavitt, Scott, Martin, Geuna, Nightingale, and Patel, 2000). While the transfer and utilization of intellectual properties such as licensing of patents via TLOs has been emphasized recently, as evidenced by the passage of the Bayh-Dole Act in the United States and similar legislations in other countries, and has been analyzed extensively (Mowery, Nelson, Sampat, and Ziedonis, 2004), intangible outputs like the formation and functioning of networks linking scientists and technologists in the private as well as public sectors have not yet been examined closely, although they would have an equally significant impact on the long-term capacity for innovation.

A historical study on the synthetic dye industry in the 19th century shows that the establishment of networks linking academia, industry, and the public sector led to the differences in educational institutions and patent laws, the key factor in explaining the technological leadership of Germany over Britain and the Untied States (Murmann, 2003). Since knowledge of synthetic organic chemistry was such a critical resource for firms in the dye industry, strong connections to the holders of this knowledge were a key variable in the long-term success of individual firms, and the network of ties that were created between academic scientists, industrialists, and government officials in Germany allowed them to build a stronger system of research and training. At the same time, the social network that connected individual players in academia, industry, and government was crucial in bringing about the changes in German patent laws concerning chemicals for their own advantage. In this way, technology and institutions coevolve through close interactions through networks linking academia, industry, and the policy sector in ways peculiar to national systems of innovation (Edquist, 2005; Lundvall, 1992; Mowery and Sampat, 2005; Nelson, 1993).

The work of Murmann is significant in the sense that it examined in detail the importance of network formation between academia, industry, and the public sector in bringing forth successful innovation. Its analysis, however, is limited to qualitative aspects of innovation networks and does not benefit fully from utilizing well-developed methods and applications of social network analysis (Carrington, Scott, and Wasserman, 2005; Wasserman and Faust, 1994). In recent years, network analysis has been undergoing a considerable progress, with significant contributions, theoretically as well as empirically, from natural scientific disciplines, especially physics (Barabasi, 2002; Watts, 2003). Building upon the work of Murmann, who conducted a detailed case study with rich historical data, it is now needed to employ a more quantitative approach to analyzing the structure and evolution of innovation networks in university-industry collaboration.

In this paper, we examine how collaboration networks involving academia, industry, the public sector are formed and functioned for the creation of innovation. This study focuses on the development of lead-free solders in the electric and electronic industry in Japan, Europe, and the United States. While traditionally lead has been used extensively for solders in electric and electronic products, the market of lead-free solders, which did not exist ten years ago, has been growing rapidly, replacing lead-containing solders. In making a transition to lead-free solders, close collaboration and coordination is indispensable among relevant actors, including material suppliers, component producers, equipment makers, product manufacturers, final users as well as universities and public institutes. We examine quantitatively the structure and evolution of research and development networks in Japan, Europe, and the United States by analyzing extensive data on the membership of research and development projects and consortia, scientific papers, and patent applications related to lead-free solders. This study illustrates how university researchers played a critical role in establishing research and development networks linking academia, industry, and the public sector and contributed to bringing forth innovation successfully through university-industry collaboration.

2. Regulatory Background on the Use of Lead-Containing Solders in Electric and Electronic Products

Regulation on the use of lead was initiated in the United States, where lead was banned in the manufacture of paint in 1978 and for solders used for joining drinking water pipework in 1986. Then in the early 1990s a series of legislations were proposed in the House of Representatives and the Senate to introduce a regulation that further releases of lead into the environment be minimized and that means be developed and implemented to reduce exposure to existing sources of environmentally dispersed lead

(Soldertec, 1998). The first such proposal, S. 2637 Lead Reduction Act, Senator Reid (1990), was intended to mandate that, one year after the date of enactment, no one be permitted to manufacture, process, or distribute in commerce any solder containing more than 0.1% lead. Although several studies were conducted on the possibility of using similar lead-free alloys in electronics, no process trials of lead-free alloys had not been performed, and specific alloys tailored to the application had to be developed. This lack of technical data on alternative technologies allowed the electronic industry to lobby against the inclusion of electronic solders in the general ban on lead, based on the main objection that no suitable lead-free alternatives were available, and various questions were also raised with regard to the impact on product cost and competitiveness, as it was generally assumed that lead-free products were more expensive than those made using lead-containing solders (Pfahl, 2005). Since an attempt to pass a revised Reid Bill (S. 729) failed in 1993, no further legislative proposals affecting specifically lead solders have been made in the Untied States. There are several states in which recycling efforts for electronics have been started, notably California, where manufacturers have to report information about reductions in the use of certain heavy metals including lead under the California Electronic Waste Recycling Act (S.B. 20/50). At the federal level, however, there is no legislation requiring the elimination of lead from electronic products.

Meanwhile, legislation directly affecting the solder and electronic industries began to be considered in Europe[1]. The first draft of the Waste Electrical and Electronic Equipment (WEEE) Directive was published in April 1998. Three months later that was followed by the publication of the second draft, which included the proposed ban on the use of lead in electronic assembly, with the schedule for the ban was to be implemented by January 2004. Then, in June 1999, a draft proposal for a WEEE directive, including the restriction of certain hazardous substances such as lead, was submitted to the business test panel as a pilot project (Commission of the European Communities, 2000). While some businesses advocated the removal or delay of the material bans, the provision on the substitution of substances was supported by NGOs, which asked for an extension of this requirement to other substances. In June 2000, the European Commission officially adopted the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive, along with the separate WEEE Directive (European Parliament and Council of the European Union,

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[1] There are also other regulations on the use of lead in some parts of Europe. Europe, Denmark, Sweden, Norway, Finland, and Iceland signed a pact to phase out lead, with Swedish manufacturers under a voluntary ban effective 2000. In 1997, the Swedish government identified lead as an element it intended to eliminate from products over the following 10 years. The Swedish Environmental Quality Objectives direct that new products, including batteries, introduced in Sweden should be mostly lead-free by 2020.

2003a, 2003b). The RoHS proposal required the substitution of lead and other various heavy metals and brominated flame retardants from January 2008. Following a conciliation process between the Council and the Parliament, in which a final implementation date of July 2006 was agreed upon, the RoHS Directive came into force in February 2003. Each member state was given 18 months to introduce the required national legislation. Some exemptions are allowed for the continued use of lead in essential applications, including lead alloys used for high-temperature soldering, and extended target dates are applied to high-reliability products such as network infrastructure.

The control of lead has been strengthened in Japan through various measures, including the review of water quality standards on lead, the strengthening of amendments to the Waste Disposal Law, and the enactment in April 2000 of the Home Appliances Recycling Law, which was originally introduced in 1998. Under this legislation, electronic devices containing lead can no longer be discarded, unless they are dealt with in proper manners. Unlike in Europe, however, legislation to regulate the use of lead in solders per se has not yet been introduced. Although the Ministry of Economy, Trade, and Industry (METI) is currently considering possible regulations with regard to lead-containing solders through discussions at a technical committee of the Council of Industrial Structure, it is likely that, rather than banning the use of lead for solders, labeling of its use in electric and electronic products for recycling is given priority, according to a report published recently by METI (2005).

3. An Analysis of Innovation Networks on Lead-Free Solders

3.1. Research and Development Projects

Following the discussions at the United States Congress on legislation for regulating the use of lead-containing solders, many research and development projects and consortia were formed to explore lead-free alternatives in Japan and Europe as well as the United States. These research and development projects included technical committees and working groups, in each of which scientists and engineers with specific expertise in university as well as industry cooperated in working on various technical issues. Through these projects, the electronics community intended to gain experience with the performance of lead-free solders to begin addressing lead-free issues, including manufacturing yield, process window for complex boards, and component compatibility.

To see the network structure of these research and development projects on lead-free solders, we conducted a network analysis of data on the membership of research and development projects. The formation of networks of organizations which participate in R&D projects or have authors of joint scientific papers is illustrated in Figure 1.

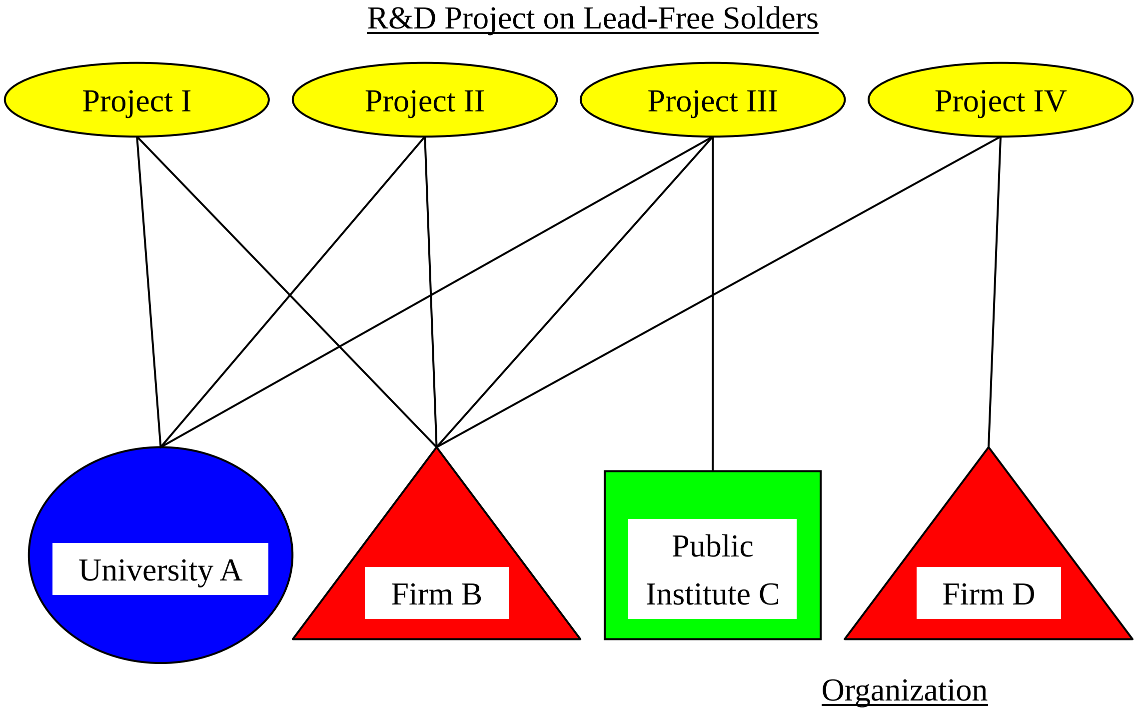

Figure 1 Schematic Illustration of Network Formation Based on Research and Development Projects and Scientific Papers on Lead-Free Solders

Initially, we obtain two-mode graphs, in which two types of node are included, that is, square nodes that represent research and development projects or scientific papers and circular nodes that stand for organizations participating in them. As the two-mode graphs do not show explicitly the ties between pairs of participating organizations linked by the projects, they need to be transformed into one-mode graphs to see inter-organizational linkages (Wasserman and Faust, 1994). The formation of a one-mode graph is illustrated in Figure 2.

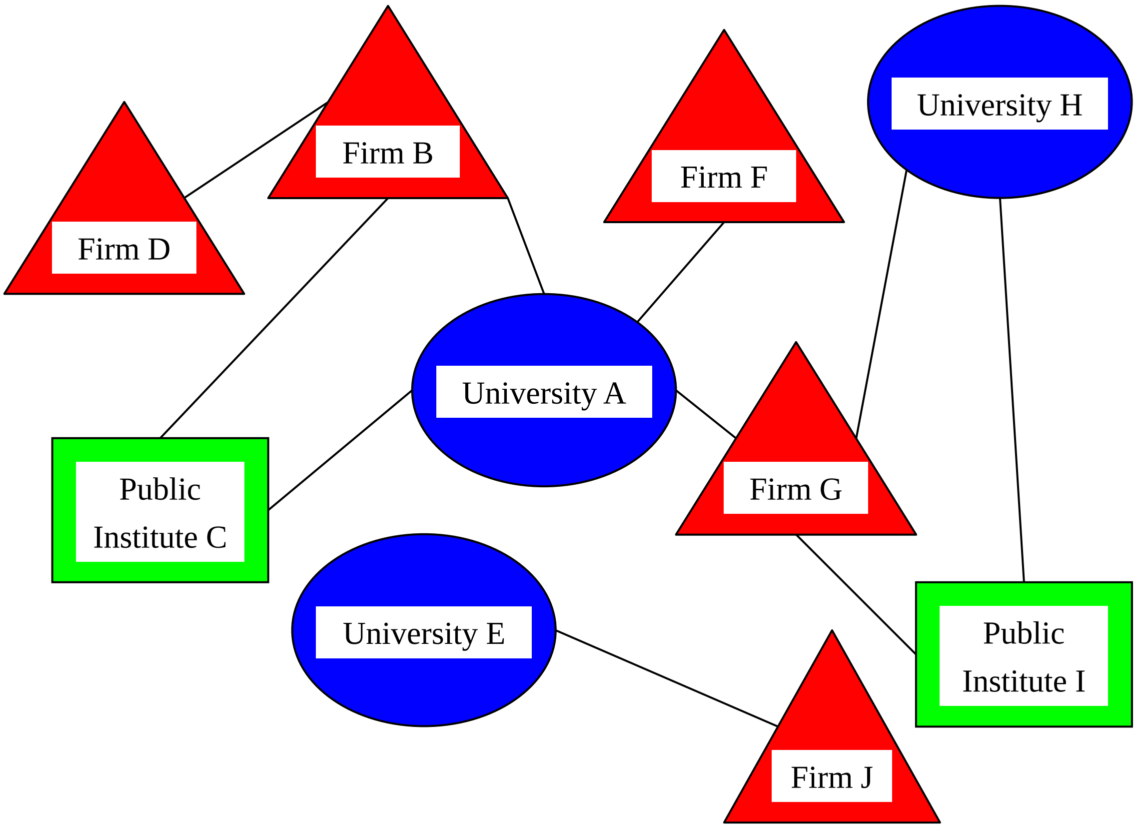

Figure 2 Interorganizational Networks Based on Research and Development Projects and Scientific Papers on Lead-Free Solders

In constructing the structure of R&D project networks in the United States, Europe, and Japan, we collected the data on the memberships of major projects on lead-free solders in the United States (Handwerker, 2003; National Center for Manufacturing Sciences, 1997, 2001), Europe (IMECAT, 2004; Management Committee of the COST Action 531, 2004; Marconi Materials Technology, 1999; National Physical Laboratory and ITRI, 1999), and Japan (Japan Electronic Industries Development Association, 2000; Japan Electronic Industries Development Association, 1998; Low-Temperature Lead-Free Solder Technology Development Project, 2002; Serizawa, Okamoto, and Shimokawa, 2002). Table 1 gives the number of research and development projects conducted in the United States, Europe, and Japan and the number of participating organizations in these projects.

Table 1 Research and Development Projects on Lead-Free Solders in the United States, Europe, and Japan (1990-2004)

	United States	Europe	Japan
Number of projects	15	16	23
Number of participating organizations	114	71	141

Figure 3, Figure 4, and Figure 5 respectively show the one-mode graphs of the research and development network on lead-free solders formed in the United States, Europe, and Japan by 1999. The blue circle nodes represent universities, the green square nodes, public research institutes, and the red triangle nodes, private companies. While each company or public research institute is represented by one node, each research laboratory, which is normally headed by a professor, is represented by one node in the case of universities, because it can be considered to have relatively high autonomy, compared with the case of companies or public research institutes. A link between two nodes shows that the two organizations participated in the same project. The thickness of a line represents the strength of the relationship between the two nodes. Hence, if two organizations participate in many research and development projects together, the line linking them becomes thicker.

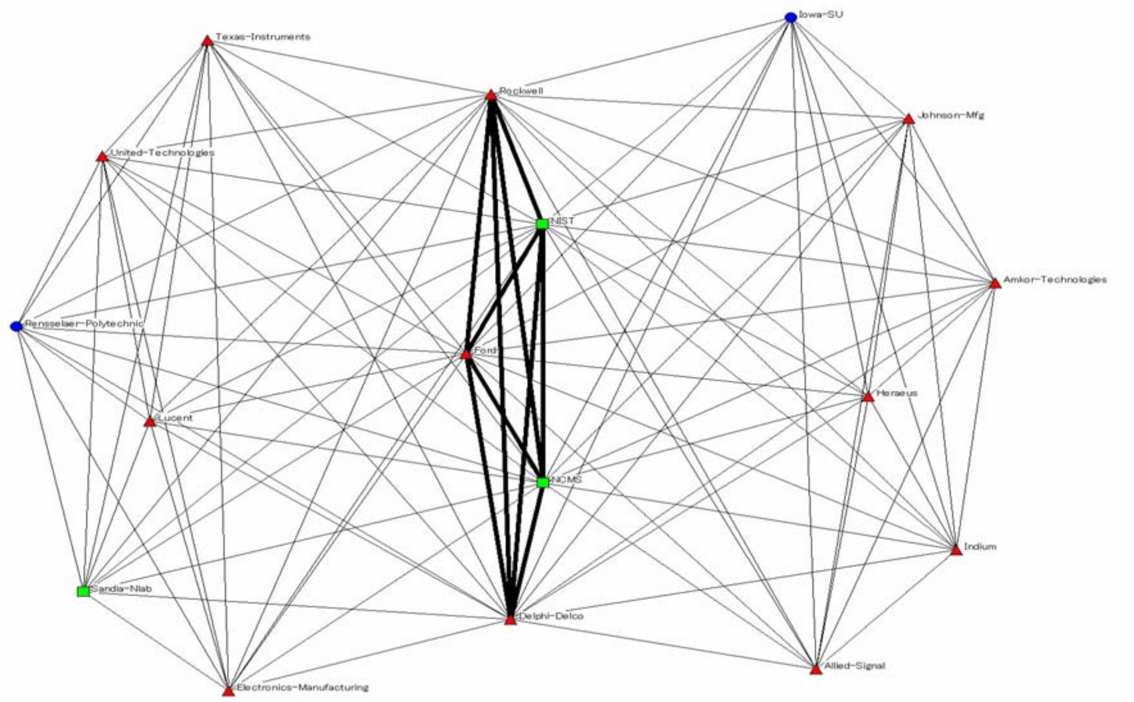

Figure 3 Network Structure of R&D Projects on Lead-Free Solders Formed in the United States by 1999

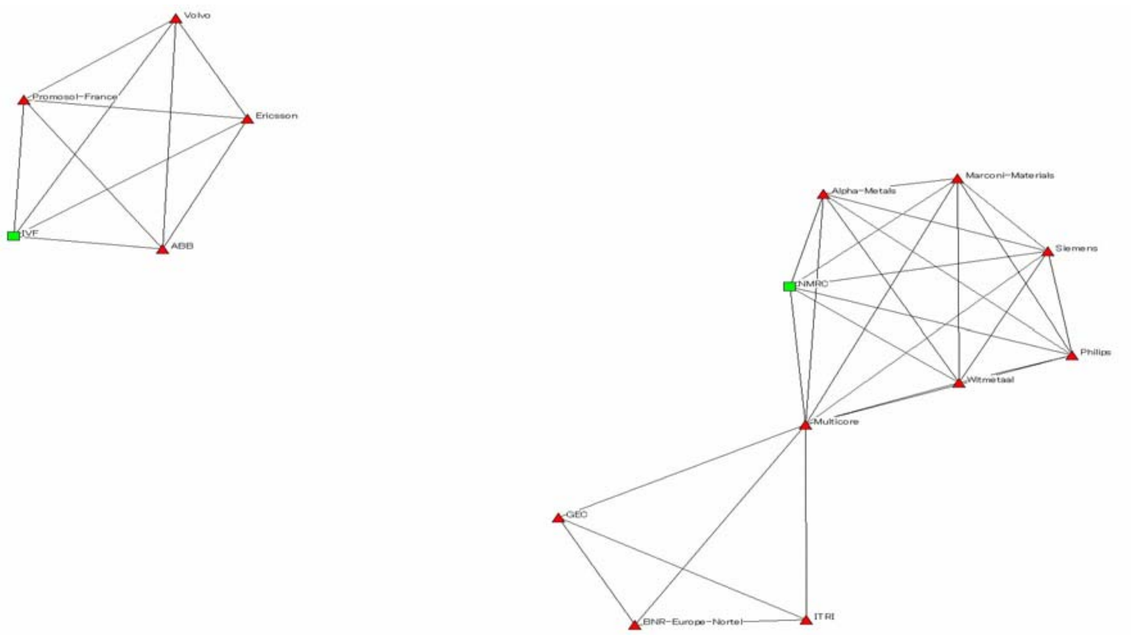

Figure 4 Network Structure of R&D Projects on Lead-Free Solders Formed in Europe by 1999

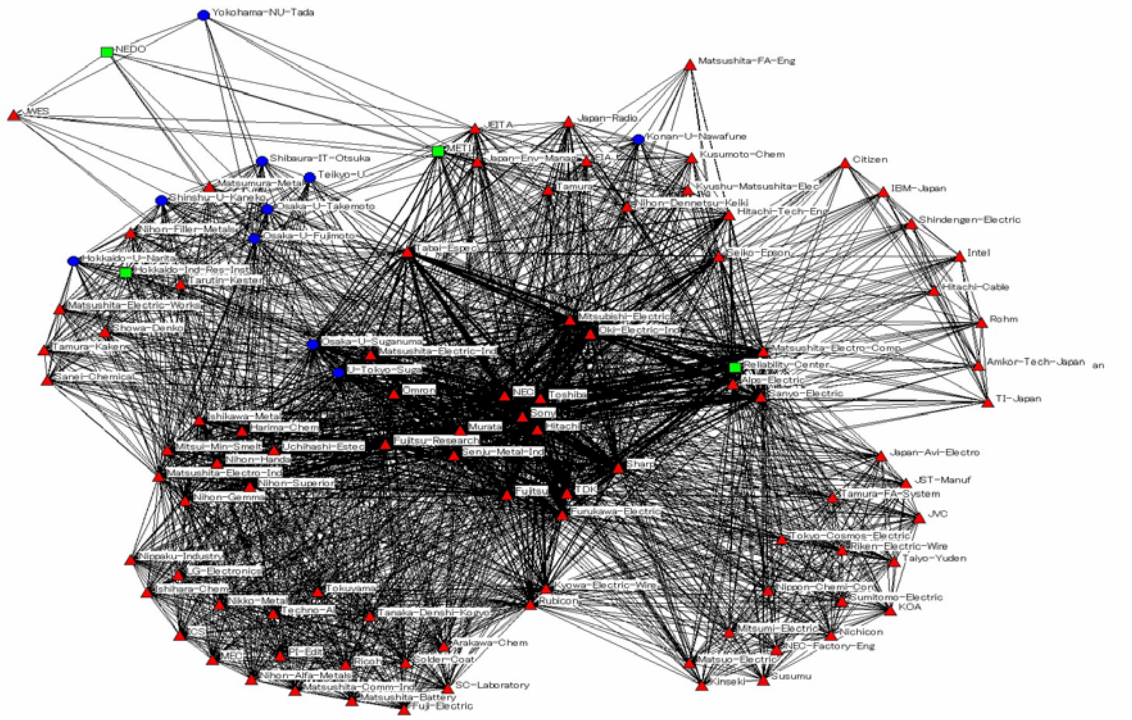

Figure 5 Network Structure of R&D Projects on Lead-Free Solders Formed in Japan by 1999

Some of the quantitative indicators on the structure of networks on R&D projects in the United States, Europe, and Japan are given in Table 2. A component of a graph is a maximal connected subgraph, the degree centrality of an actor is the number of edges it has, and network degree centralization is an index to determine how centralized the degree of the set of actors and can also be used as a measure of the dispersion or range of the actor degree. The network degree centralization reaches its maximum value of 1 when one actor chooses all other actors, and the other actors interact only with this one, central actor, exactly the situation in a star graph, and attains its minimum value of 0 when all degrees are equal, exactly the situation realized in a circle graph (Wasserman and Faust, 1994). The network degree centralization measures the range or variability of the individual actor degree, whereas the average degree centrality is among quantifications of average actor tendencies, rather than variability.

Interactions between two non-adjacent actors might depend on the other actors in the set of actors, especially the actors who lie on the paths between the two (Wasserman and Faust, 1994). The indicator of betweenness centrality is that an actor is central if it lies between other actors on their shortest paths, implying that to have a large value of betweenness centrality, the actor must be between many of the actors via their shortest paths. We can then normalize this measure by expressing it as a percentage of the maximum possible betweenness that an actor could have had (Hanneman and Riddle, 2005).

Table 2 Quantitative Characteristics of the Networks on R&D Projects Formed in the United States, Europe, and Japan by 1999

	U.S.	Europe	Japan
Number of Nodes	17	15	104
Number of Edges	110	37	2,861
Number of Components	1	2	1
Average Degree Centrality	12.9	4.9	55.0
Network Degree Centralization	0.26	0.32	0.20
Average Betweenness Centrality (University)	0	0	28.3
(Public Institute)	4.8	0	14.0
(Private Firm)	1.8	1.4	30.9

The structure of the network of research and development projects formed in Europe is fragmented into two components, with no linkages between them, whereas that of the United States are connected, but the links among the nodes are relatively sparse. In contrast, the structure of the Japanese innovation network is dense, and the number of the nodes included in the network is by far the largest, and they are well connected, with much more ties between them than the US or European network. These figures of network structure suggest that a dense network, involving relevant actors in academia, industry, and the public sector, was formed at a relatively early stage in Japan, compared with those in the United States and Europe.

Organizations with large values of betweenness centrality in the networks of research and development projects formed in the United States, Europe, and Japan by 1999 are listed in Table 3, Table 4, and Table 5, respectively. Organizations written in bold letters are universities, and those in italics are public institutes, with the remaining organizations being private firms.

Table 3 Organizations with Large Betweenness Centrality in the Network on R&D Projects Formed in the United States by 1999

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Ford	7.20	4.71
NCMS	7.20	4.71
Delphi-Delco	7.20	4.71
NIST	7.20	4.71
Rockwell	7.20	4.71

Table 4 Organizations with Large Betweenness Centrality in the Network on R&D Projects Formed in Europe by 1999

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Multicore	18.0	13.2

Table 5 Organizations with Large Betweenness Centrality in the Network of R&D Projects Formed in Japan by 1999

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Toshiba	249.3	4.75
Sony	234.2	4.46
NEC	234.2	4.46
Hitachi	234.2	4.46
Fujitsu	176.7	3.36
Murata	164.2	3.13
Mitsubishi Electric	160.4	3.05
Senju Metal Industry	151.7	2.89
Sharp	150.1	2.86
Oki Electric Industry	148.9	2.84
University of Tokyo, Suga	100.0	1.90
Osaka University, Suganuma	100.0	1.90

TDK	94.0	1.79
Furukawa Electric	84.4	1.61
Matsushita Electric Industry	82.3	1.57
Matsushita Electronic Components	63.6	1.21
Sanyo Electric	56.1	1.07
Rubicon	45.8	0.87
Kyowa Electric Wire	45.8	0.87
Osaka University, Takemoto	41.7	0.79
Osaka University, Fujimoto	41.7	0.79
Tabai Espec	38.4	0.73
Omron	37.9	0.72

In terms of betweenness centrality, research laboratories headed by university professors, namely, Professor Suga of the University of Tokyo and Professors Suganuma, Takemoto, and Fujimoto of Osaka University, occupy important positions in the Japanese network. That would suggest that these actors in academia, along with large electronic manufacturers such as Toshiba, Sony, NEC, Hitachi, and Fujitsu, have functioned as information hubs or coordinators among relevant actors. In the case of the United States, on the other hand, public institutes/organizations such as the National Center for Manufacturing Sciences (NCMS) and the National Institute of Standards and Technology (NIST) are positioned at important places in terms of betweenness centrality.

Then we constructed research and development project networks on lead-free solders which had been formed by 2004 in the Untied States, Europe, and Japan. As in the case of the networks formed by 1999, two-mode graphs are transformed into one-mode graphs, which are shown in Figure 6, Figure 7, and Figure 8.

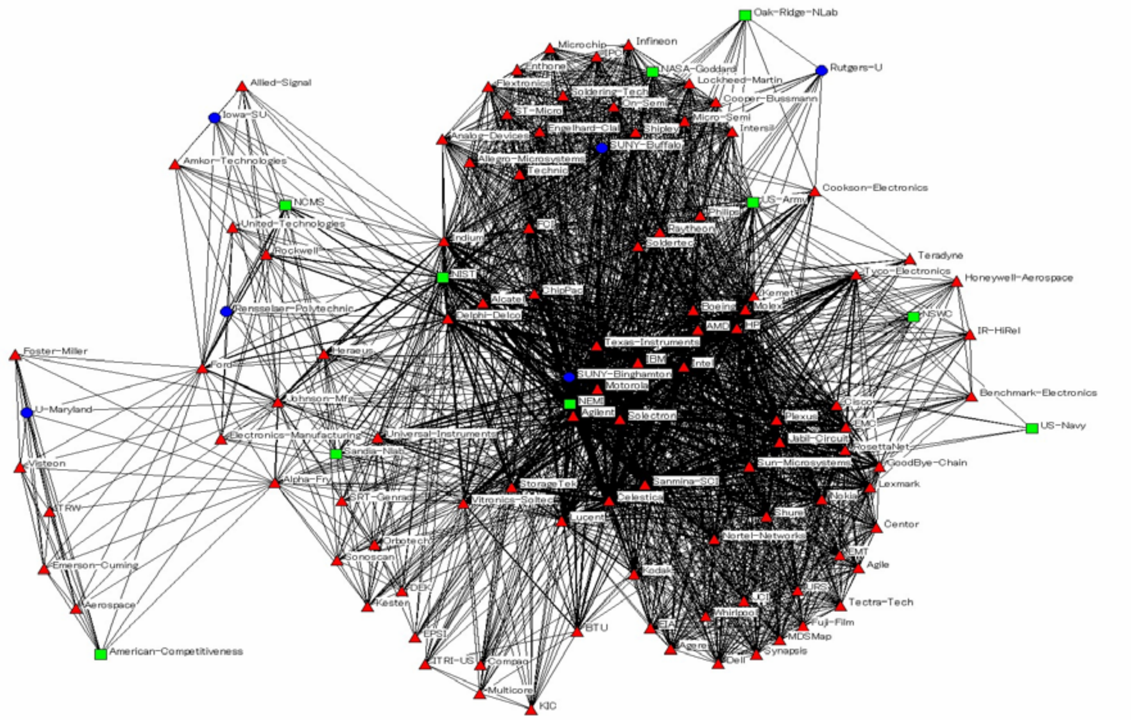

Figure 6 Network Structure of R&D Projects on Lead-Free Solders Formed in the United States by 2004

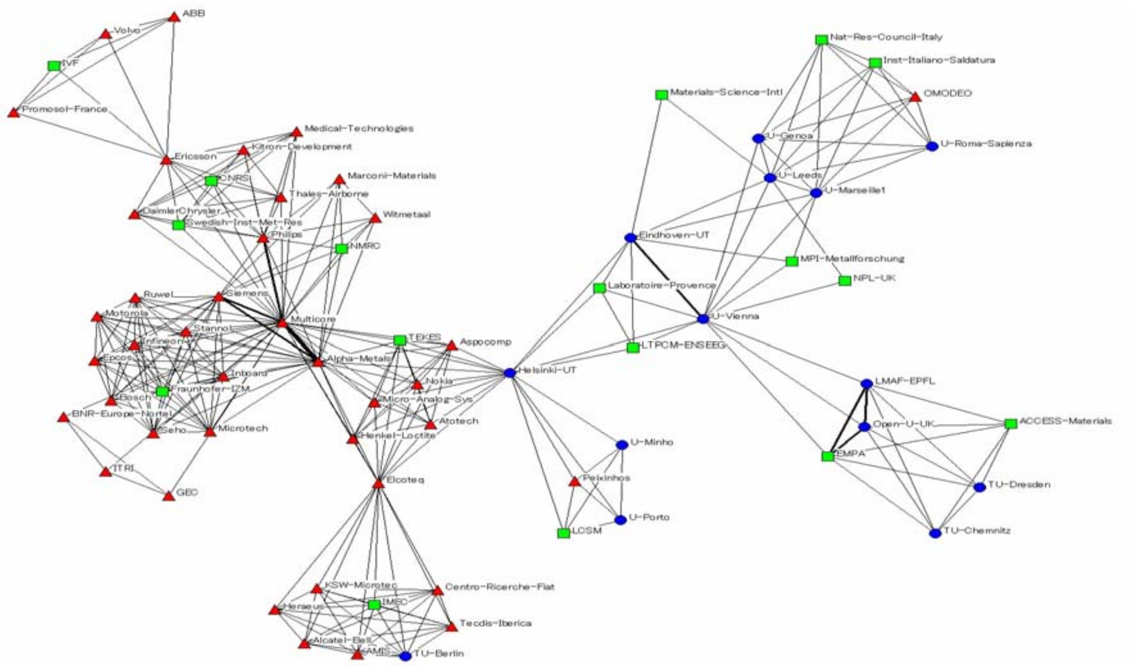

Figure 7 Network Structure of R&D Projects on Lead-Free Solders Formed in Europe by 2004

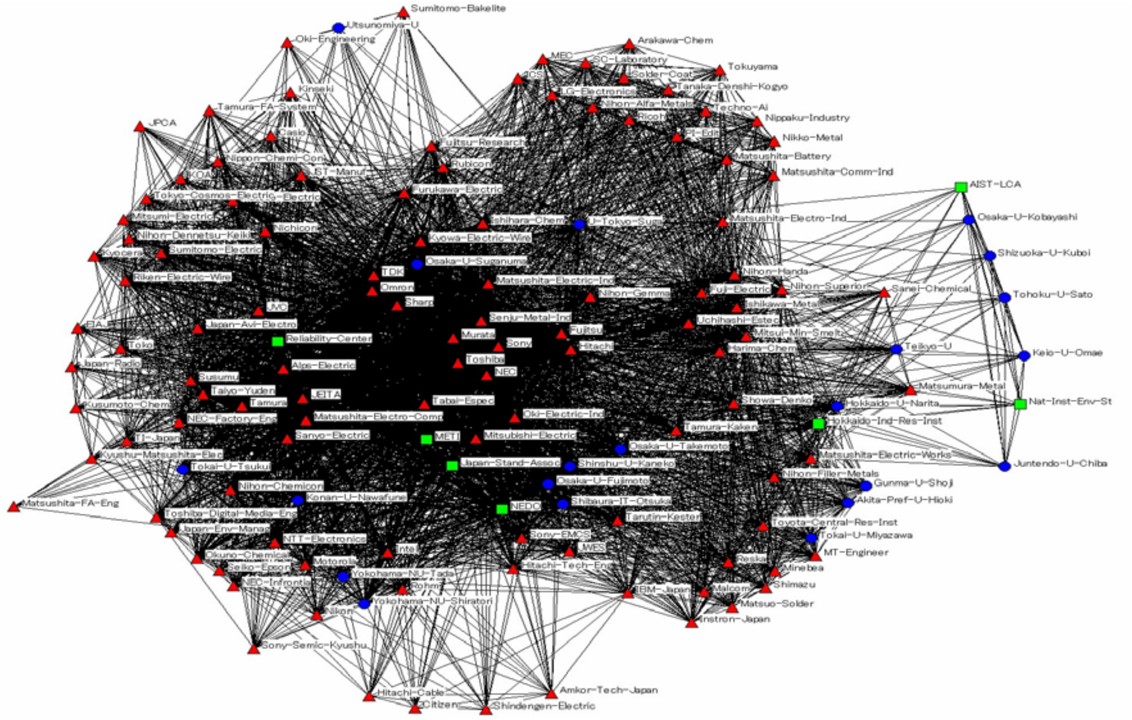

Figure 8 Network Structure of R&D Projects on Lead-Free Solders Formed in Japan by 2004

In the case of the U.S. and Japanese networks, the majority of the participants are companies, with several universities and public research institutes well connected, whereas there are the numbers of companies, universities, and public research institutes which participated in the network are almost equal. There figures of innovation network suggest that the Untied States had almost caught up Japan in terms of the entrance of participants in the R&D community and the density of linkages among them by 2004. In Europe, although the network has grown since 2000, there are basically two parts, which are relatively separate, with companies mostly participating in one part and universities in the other. Since innovation on lead-free soldering technologies would require close and delicate coordination among solder materials, production process, measurement equipment, and final products, the lack of industry-wide cooperation could have resulted in inadequate and delayed development and adoption of lead-free soldering technologies in Europe.

As in the case of networks formed by 1999, Table 6 gives some of the quantitative indicators of the structure of R&D project networks formed by 2004 in the United States, Europe, and Japan.

Table 6 Quantitative Characteristics of the Networks on R&D Projects Formed in the United States, Europe, and Japan by 2004

	U.S.	Europe	Japan
Number of Nodes	114	71	141
Number of Edges	3,180	307	7,973
Number of Components	1	1	1
Average Degree Centrality	55.8	8.6	113.1
Network Degree Centralization	0.15	0.12	0.17
Average Betweenness Centrality (University)	31.5	178.7	32.6
(Public Institute)	55.4	3.8	46.5
(Private Firm)	41.0	55.1	42.5

The network structure of research and development projects on lead-free solders in Japan is very dense, involving almost 8,000 links among 141 participating organizations. As there is only one component in the graph, all the nodes included in the network are connected. The network degree centralization is 0.17, implying that the network structure is relatively less concentrated. These findings suggest that information and knowledge could be shared effectively through the multiple linkages among the relevant actors, including universities, solder suppliers, components producers, and electronic equipment manufacturers. Since the development and implementation of lead-free soldering technologies would require close collaboration and coordination among solder materials, production process, measurement equipment, and final products, the existence of wide-range cooperation worked effectively in developing and adopting lead-free soldering technologies in Japan.

Organizations with large values of betweenness centrality in the R&D networks formed in the United States, Europe, and Japan by 2004 are given in Table 7, Table 8, and Table 9, respectively.

Table 7 Organizations with Large Betweenness Centrality in the Network of R&D Projects Formed in the Untied States by 2004

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Johnson Manufacturing	342.7	4.22
Texas Instruments	296.6	3.65

IBM	286.4	3.52
Alpha Fry	282.0	3.47
NIST	270.2	3.33
Delphi Delco	254.8	3.14
Solectron	246.7	3.04
Motorola	237.6	2.92
NEMI	229.8	2.83
Agilent	222.2	2.73
Intel	194.5	2.39
Celestica	187.7	2.31
SUNY-Binghamton-IEEC	181.7	2.24
Indium	173.9	2.14
Ford	146.8	1.81
Lucent	144.3	1.78
Sanmina-SCI	142.9	1.76
HP	111.6	1.37
Alcatel	81.2	1.00
Molex	70.0	0.86
AMD	63.0	0.78
StorageTek	59.3	0.73
Boeing	56.5	0.70
Kemet	48.5	0.60
ChipPac	46.1	0.57
US Army	30.6	0.38
Heraeus	30.5	0.38
Vitronics Soltec	27.3	0.34
Jabil Circuit	26.1	0.32
Plexus	26.1	0.32
FCI Electronics	24.8	0.31
Raytheon	18.2	0.22

Table 8 Organizations with Large Betweenness Centrality in the Network of R&D Projects Formed in Europe by 2004

Organization	Betweenness	Normalized Betweenness

	Centrality	Centrality (%)
Helsinki University of Technology	1184.0	32.4
Multicore	1091.8	29.9
University of Vienna	700.4	19.2
Elcoteq	496.0	13.6
Alpha Metals	313.3	8.57
Ericsson	264.0	7.22
Eindhoven University of Technology	222.6	6.09
University of Leeds	112.0	3.06
University of Marseille	101.3	2.77
EMPA	65.0	1.78
Open University, UK	65.0	1.78
LMAF-EPFL	65.0	1.78
University of Genoa	51.7	1.42
Philips	27.5	0.75
Siemens	13.3	0.37

Table 9 Organizations with Large Betweenness Centrality in the Network of R&D Projects Formed in Japan by 2004

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Hitachi	444.7	4.57
Fujitsu	346.9	3.57
Oki Electric Industry	338.6	3.48
Toshiba	330.5	3.40
NEC	312.6	3.21
Sony	303.2	3.12
Senju Metal Industry	259.6	2.67
Murata	238.8	2.45
University of Tokyo, Suga	180.8	1.86
Tabai Espec	169.8	1.75
TDK	169.3	1.74
Osaka University, Takemoto	155.5	1.60

Mitsubishi Electric	140.4	1.44
Matsushita Electric Industry	134.3	1.38
Sharp	133.8	1.38
Osaka University, Suganuma	116.6	1.20
Omron	113.6	1.17
Nihon Gemma	110.7	1.14
Kyowa Electric Wire	87.7	0.90
METI	83.1	0.85
Matsushita Electronic Components	74.8	0.77
Japan Standard Association	73.3	0.75
Reliability Center for Electronic Components of Japan	66.8	0.69
Sanyo Electric	65.6	0.67
Furukawa Electric	65.4	0.67
Hokkaido Industrial Research Institute	57.3	0.59
Hokkaido University, Narita	57.3	0.59
Alps Electric	50.8	0.52
Osaka University, Fujimoto	49.0	0.50
Shinshu University, Kaneko	47.3	0.49
Shibaura Institute of Technology, Otsuka	47.0	0.48
NEDO	45.2	0.47
Mitsui Mining and Smelting	43.7	0.45
Nihon Superior	43.7	0.45
Uchihashi Estec	43.7	0.45

As can be seen, large electronic companies in the private sector, such as Hitachi, Fujitsu, Oki Electric Industry, Toshiba, NEC, Sony, Mitsubishi Electric, and Matsushita Electric Industry, have relatively large values of betweenness centrality, suggesting that they would be major players working between solder manufacturers, metal makers, and component suppliers. Note also that the list includes the same university laboratories as in the network formed by 1999, along with several other laboratories led by professors in other universities. Among organizations with large values of betweenness centrality are METI and NEDO in the public sector. Thus, we could argue that the network structure of research and development projects in Japan, which included major players in the public as well as private sectors at relatively central positions, has contributed to facilitating close public-private partnership for implementing innovation on lead-free soldering technologies.

The structure of the U.S. network exhibits similar characteristics as those in the Japanese network in terms of the number of nodes and linkages. The list of organizations with large values of betweenness centrality indicates, however, that universities play a relatively minor role in the United States. Instead, public research institutes, notably NIST and National Electronics Manufacturing Initiative (NEMI)[2], are major actors, centrally positioned among mostly large private companies, including Texas Instruments, IBM, Motorola, and Intel. In the case of Europe, while the network contains numerous universities and public research institutes with relatively high values of betweenness centrality, such as the Helsinki University of Technology and the University of Vienna, its structure which is basically separated into two parts implies that communication and coordination between university laboratories and private companies would not be implemented effectively. Although large companies such as Philips and Siemens were achieving implementation of lead-free soldering in Europe, there was no pan-European industry forum involving small- and medium-sized enterprises (SMEs), and coherent information network or technology or research provider network did not exist in Europe or the United States at that time.

3.2. Publication of Scientific Papers on Lead-Free Solders

As indicators of innovative outputs, scientific papers related to lead-free solders are also analyzed. We used the database of the Science Citation Index, which has been assembled and maintained by Thomson Scientific. To collect papers that are related to lead-free solders, we picked up those papers that include in the title, abstract, or keywords the phrase, lead-free solder*, which could be lead-free solder, solders, or soldering. Our dataset contains relevant papers published between 1990 and 2004. The trends in the publication of scientific papers by authors belonging to organizations in the United States, Europe, and Japan are given in Figure 9.

The total number of papers related to lead-free solders published from 1990 to 2004 was 564. There were very few papers which were published in the early 1990s. Then the number of published papers showed a small increase in the middle of the

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[2] NEMI is an industry-led consortium composed of approximately 70 electronics manufacturers, suppliers, associations, government agencies, and universities. Although NEMI was originally organized as a North American Group, it has expanded its geographical focus and officially changed its name to International Electronics Manufacturing Initiative (iNEMI) in 2004, reflecting its more international memberships. In this paper we keep to use the name of NEMI for consistency.

1990s, when there were discussions on possible regulations on the use of lead at the US Congress. After a decline, the publication of scientific papers on lead-free solders started to rise again in the late 1990s, as the European Commission started to discuss the introduction of the RoHS directive. Since then, the number of paper publications has continued to increase rapidly in the United States and Japan, and in Europe to a lesser extent.

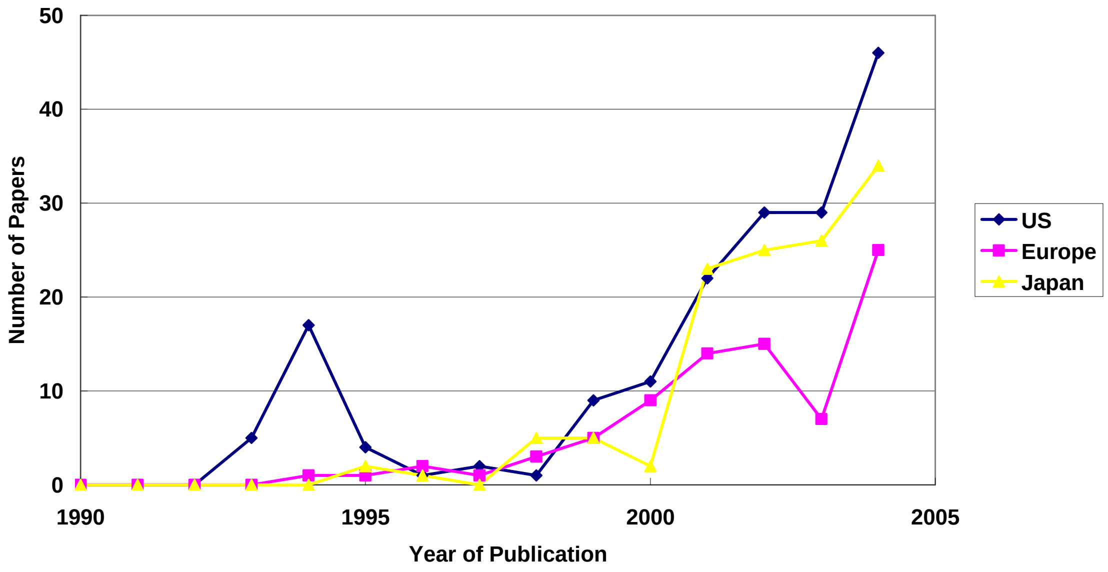

Figure 9 Publication of Scientific Papers on Lead-Free Solders in the U.S., Europe, and Japan (1990-2004)

By using this data set, we could formulate the networks of organizations to which the authors of joint scientific papers on lead-free solders belong. In constructing the network, those organizations which have only authors who have never published scientific papers jointly with authors belonging to other organizations are put on the left-upper corner, as our current interest is in examining inter-organizational collaborations. The networks which had been formulated by 1999 in the United States, Europe, and Japan are shown in Figure 10, Figure 11, and Figure 12, respectively. Some of the quantitative characteristics of these networks are given in Table 10.

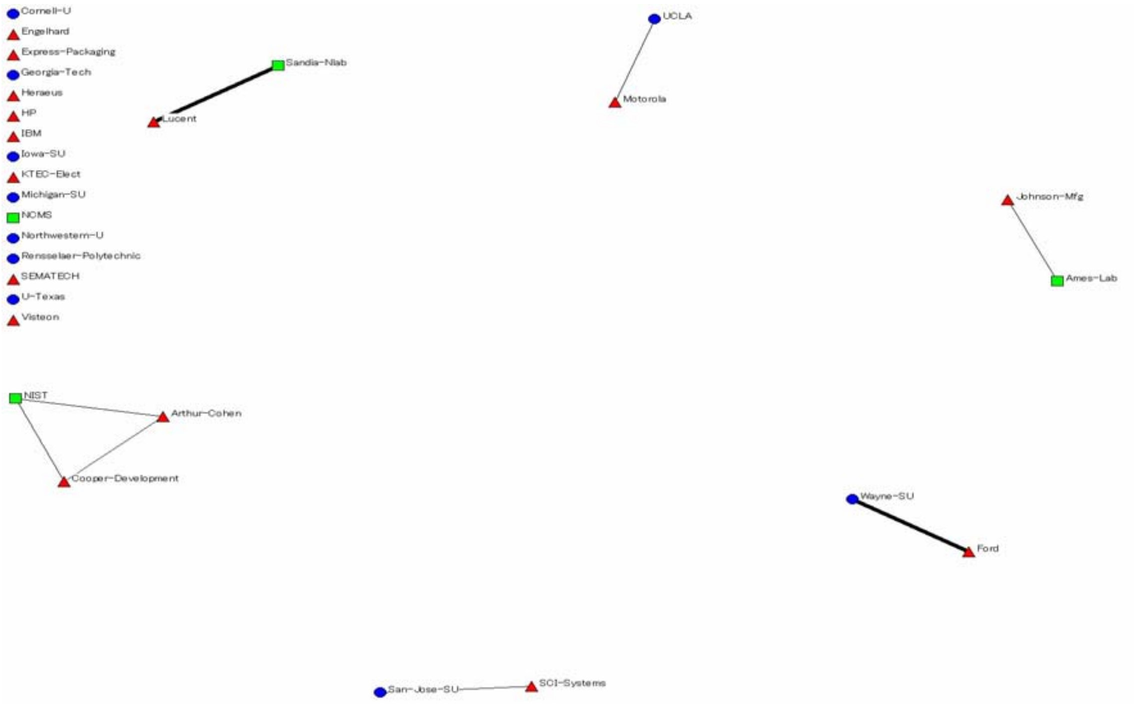

Figure 10 Network Structure of Scientific Papers on Lead-Free Solders Formed in the United States by 1999

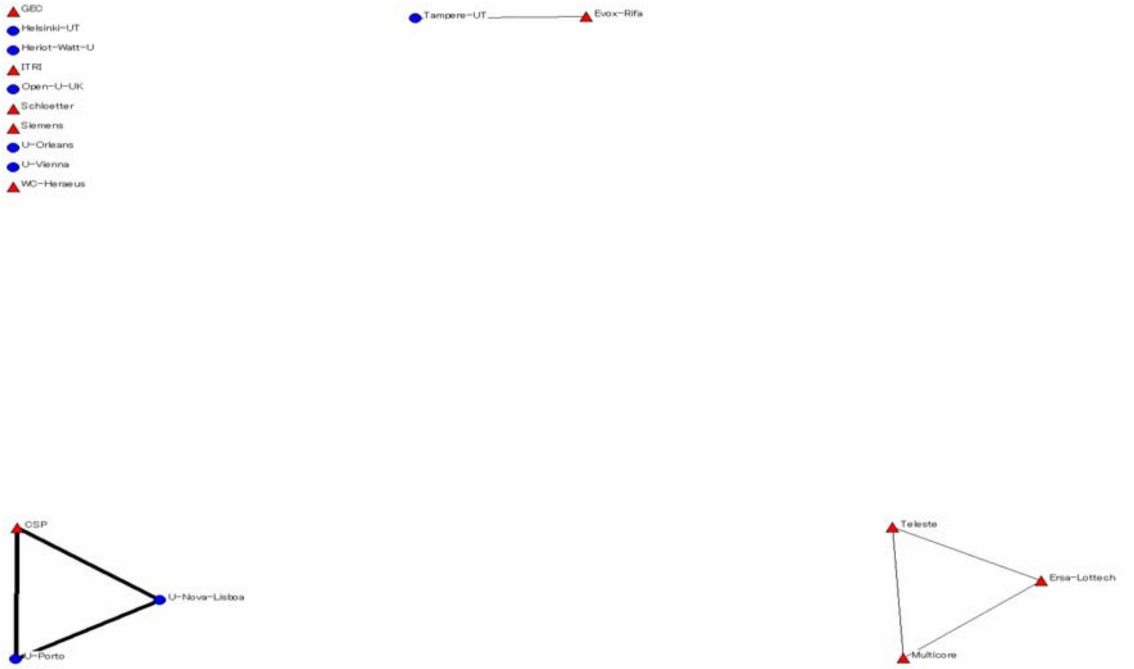

Figure 11 Network Structure of Scientific Papers on Lead-Free Solders Formed in Europe by 1999

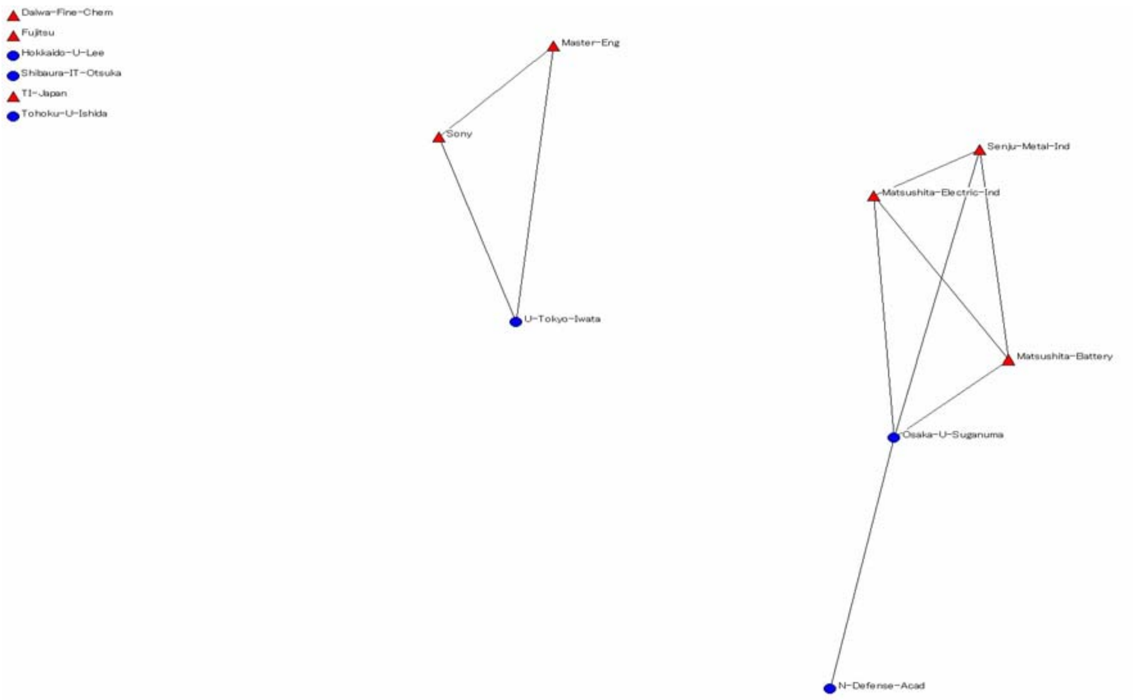

Figure 12 Network Structure of Scientific Papers on Lead-Free Solders Formed in Japan by 1999

Table 10 Quantitative Characteristics of the Networks on Scientific Papers Formed in the United States, Europe, and Japan by 1999

	U.S.	Europe	Japan
Number of Nodes	29	19	14
Number of Edges	10	10	10
Number of Components	22	13	8
Number of Nodes in the Largest Component (%)	3 (10%)	4 (21%)	5 (36%)
Average Degree Centrality	0.69	1.1	1.4
Network Degree Centralization	0.03	0.09	0.23
Average Betweenness Centrality (University)	0	0.06	0.5
(Public Institute)	0	0	0
(Private Firm)	0	0.05	0

In a similar way, the networks formulated by 2004 in the United States, Europe, and Japan are shown in Figure 13, Figure 14, and Figure 15, respectively.

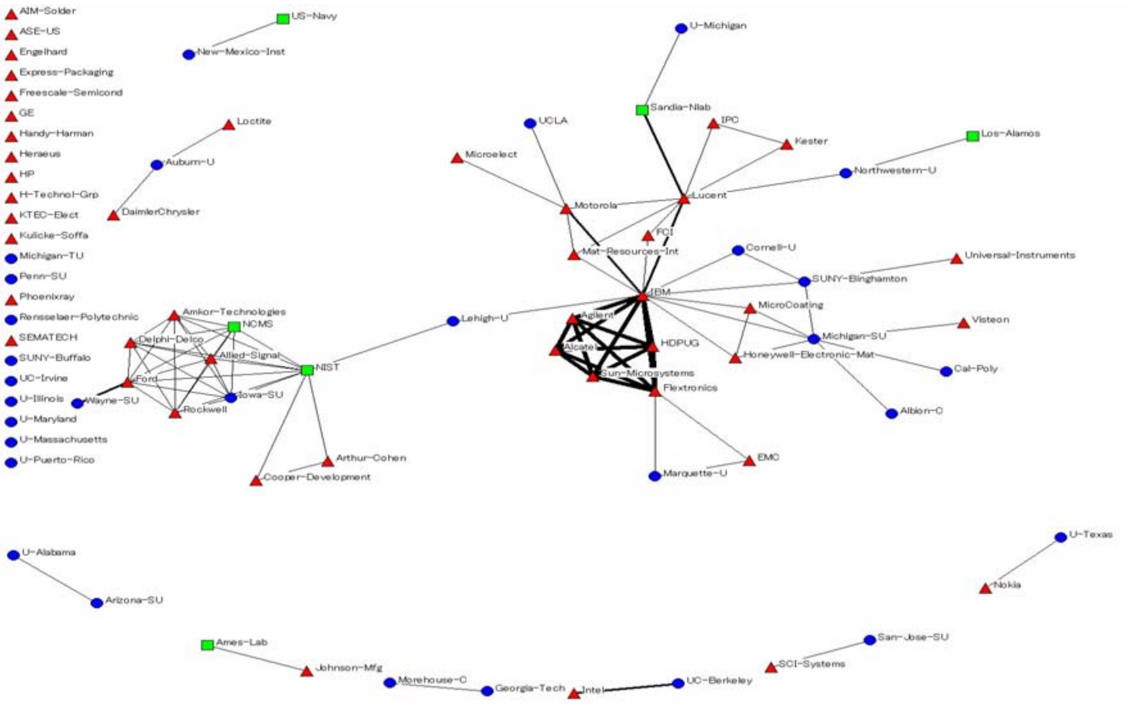

Figure 13 Network Structure of Scientific Papers on Lead-Free Solders Formed in the United States by 2004

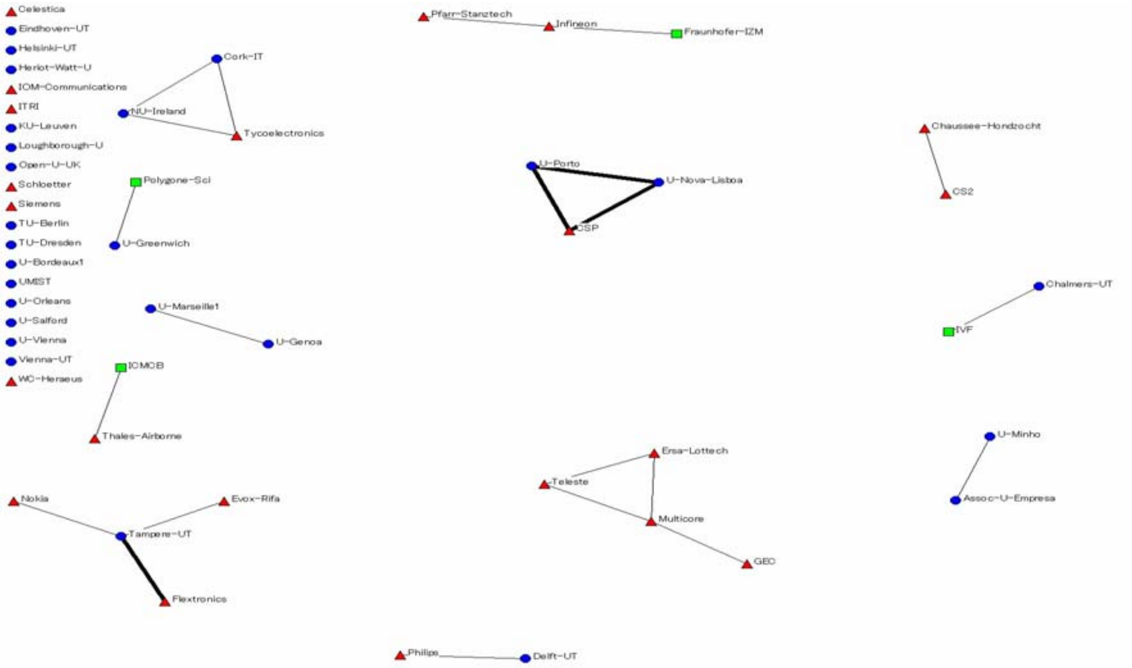

Figure 14 Network Structure of Scientific Papers on Lead-Free Solders Formed in Europe by 2004

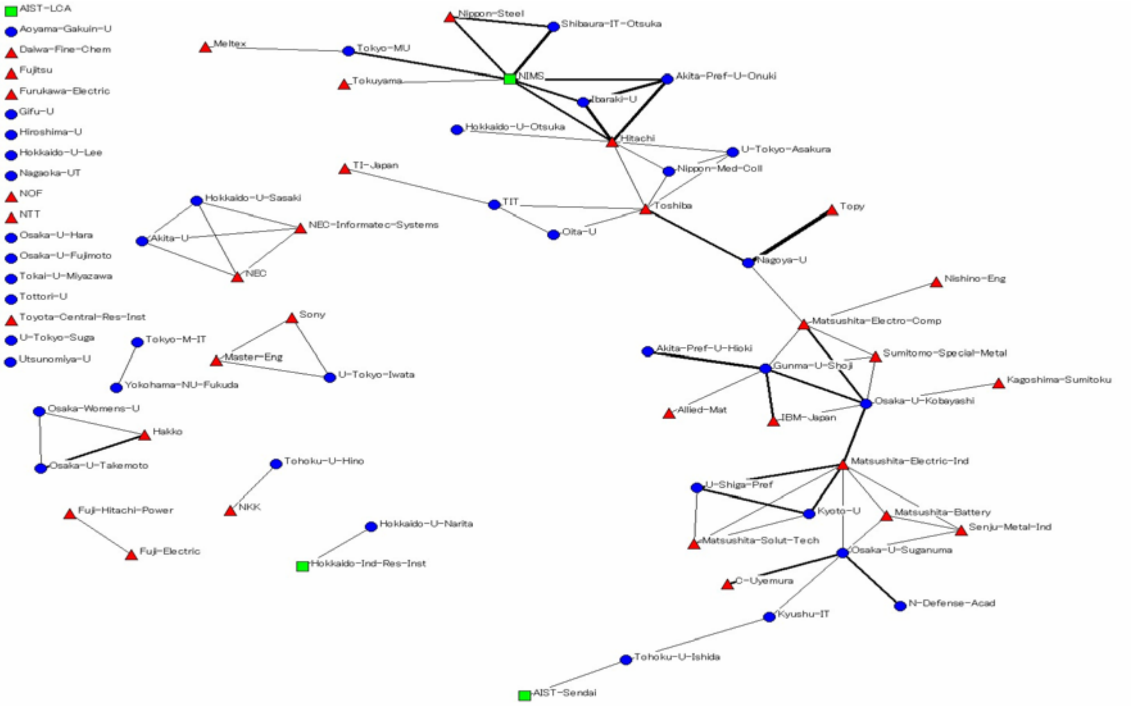

Figure 15 Network Structure of Scientific Papers on Lead-Free Solders Formed in Japan by 2004

While we could see a large cluster involving universities, companies, and public institutes in the cases of the United States and Japan, the figure for Europe evidently shows fragmentation of the network structure with many small clusters, each of which contains only a few organizations. As in the case of the networks based on research and development projects, some of the quantitative characteristics of the networks are given in Table 11.

Table 11 Quantitative Characteristics of the Networks on Scientific Papers Formed in the United States, Europe, and Japan by 2004

	U.S.	Europe	Japan
Number of Nodes	81	53	66
Number of Edges	142	30	98
Number of Components	32	32	20
Number of Nodes in the Largest Component (%)	41 (51%)	5 (9%)	41 (62%)
Average Degree Centrality	3.5	1.1	3.0
Network Degree Centralization	0.09	0.03	0.04
Average Betweenness Centrality (University)	33.3	0.17	49.1

(Public Institute)	108.5	0	61.0
(Private Firm)	41.7	0.19	29.7

In general, the number of organizations participating in the networks of scientific papers is smaller than that for the networks of research and development projects, although more universities are represented in the co-authorship networks compared with the research and development networks. In the case of Japan, the entire network of scientific papers is smaller than that of research and development projects, with much smaller actors and linkages among them. The network started to have clusters at an early stage, and a very large cluster has been formed by 2004, involving mainly universities and companies together along with several public research institutes, which accounts for 80% of the nodes included in the whole network. It can be seen that in writing scientific papers on lead-free papers, there are many cases of collaboration between universities and companies, both of which are almost equally represented in the co-authorship network. The U.S. network exhibits similar characteristics, although there are more nodes with dense linkages among them, in sharp contrast to the fragmented network formed in Europe. Table 12, Table 13, and Table 14 show organizations with higher values of betweenness centrality in the networks in the United States, Europe, and Japan, respectively.

Table 12 Organizations with Large Betweenness Centrality in the Network of Scientific Papers Formed in the United States by 2004

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
IBM	1142.0	18.1
Lehigh University	616.0	9.75
NIST	612.0	9.68
Lucent	360.0	5.70
Michigan State University	226.0	3.58
Motorola	150.0	2.37
Flextronics	148.0	2.34
SUNY-Binghamton	80.0	1.27
Ford	76.0	1.20
Northwestern University	76.0	1.20

Sandia National Laboratory	39.0	0.62
Auburn University	2.0	0.03

Table 13 Organizations with Larger Betweenness Centrality in the Network of Scientific Papers Formed in Europe by 2004

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Tampere University of Technology	3.0	0.226
Multicore	2.0	0.151
University of Porto	1.5	0.113
CSP	1.5	0.113
Infineon	1.0	0.075

Table 14 Organizations with Large Betweenness Centrality in the Network of Scientific Papers Formed in Japan by 2004

Organization	Betweenness Centrality	Normalized Betweenness Centrality (%)
Osaka University, Faculty of Engineering	380.8	18.3
Matsushita Electric Industry	363.0	17.5
Gunma University	287.2	13.8
Akita Prefectural University	254.3	12.2
Osaka University, Institute of Scientific and Industrial Research	213.0	10.2
Hitachi	201.3	9.7
National Institute for Materials Science (NIMS)	183.0	8.8
Matsushita Electronic Components	164.7	7.9
Toshiba	162.0	7.8
Nagoya University	141.7	6.8
Kyushu Institute of Technology	111.0	5.3
Tohoku University	77.0	3.7

Hokkaido University	76.0	3.7
Tokyo Metropolitan University	39.0	1.9
Tokyo Institute of Technology	39.0	1.9

While there are several large electronic companies such as Matsushita Electric Industry and Hitachi in the list for the Japanese network, universities and public research institutes are relatively better positioned in terms of betweenness centrality, notably, Osaka University and the National Institute for Materials Science. At the Graduate School of Engineering of Osaka University, Professor Fujimoto, who has a large value of betweenness centrality in the network structure of research and development projects, is conducting research on lead-free solders, and the Institute of Scientific and Industrial Research of Osaka University has Professor Suganuma as a faculty member. This suggests that universities and public research institutes play a crucial role in establishing collaboration networks of scientific papers, possibly facilitating the flow of scientific knowledge and technical information in the research community on lead-free solders in Japan. In the case of the United States, while many universities are included in the list as in the Japanese network, private companies such as IBM, Lucent, and Motorola, along with NIST, also occupy important positions in the co-authorship network. The European networks of the early and late stages contain organizations whose number is not so small compared with that of the Japanese networks. The network structure of Europe in 2004 exhibits a significant degree of fragmentation, in sharp contrast to the structure of the U.S. and Japanese networks in the same period.

3.3. Outputs of R&D Activities on Lead-Free Solders

As an indicator of the outputs of R&D activities, we examined patents related to lead-free solders. Since there are major differences among countries in procedures and criteria for granting patents (Patel and Pavitt, 1995), international comparisons are most reliable when international patenting or patenting in one country is used. We used data on U.S. patents in this paper because companies not only in the United States but also those in Japan and Europe would be reasonably expected to have strong incentives to obtain patent protection in the largest market in the world for their technologies. Data was obtained from the web-based patent database of the US Patent and Trademark Office[3]. This database contains patents which have been issued since January 1, 1976.

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[3] URL: http://www.uspto.gov.

We picked up those patents which include in the title, abstract, or keywords the phrase, lead-free solder*, in a similar manner to the case of scientific papers. Only those patents which were published by the end of 2005 are included in our data set. Figure 16 shows the trends in the US patents on lead-free soldering technologies with assignees in the United States, Japan, and Europe.

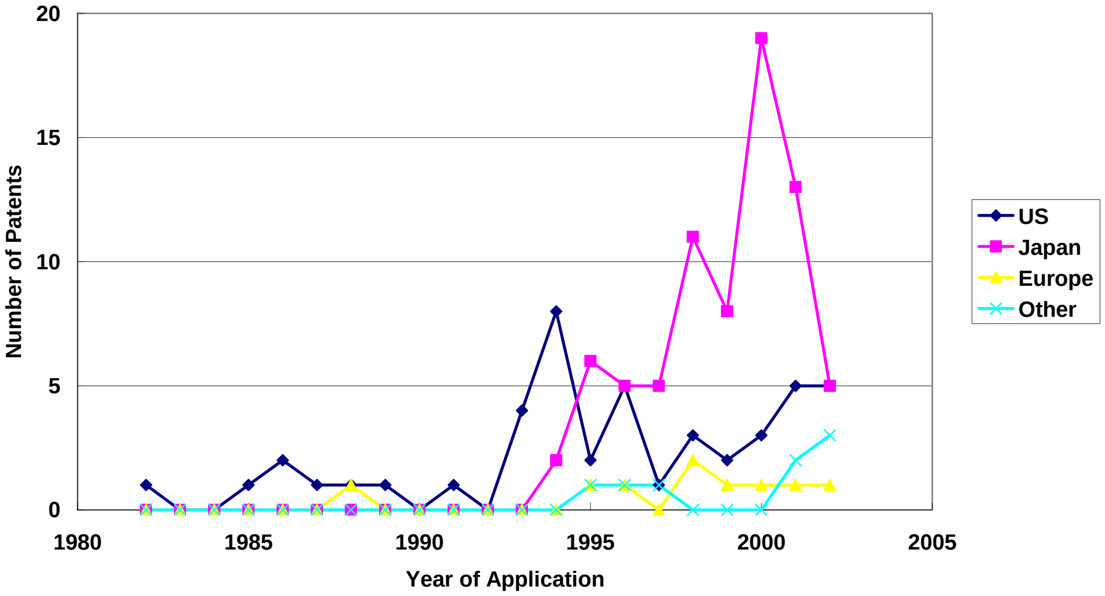

Figure 16 US Patents on Lead-Free Solders with Assignees in the United States, Japan, and Europe

In the 1980s, there were a small number of patents on technologies related to lead-free soldering, most of which were granted to those in the United States. Then the number of patents applied for by U.S. firms jumped in the early 1990s, when. As the legislative move to regulate the use of lead waned, patent applications by U.S. firms declined rather quickly in the middle of the 1990s. On the other hand, patent applications by Japanese firms started to increase a few years later and continued to grow overall in the second half of the 1990s. It is suggested in this figure that the early start in Japan in establishing collaborative networks for R&D activities on lead-free solders in the middle of the 1990s resulted in successful patent applications related to lead-free solders. While the figure indicates that patent applications by Japanese firms have declined significantly since 2000s, that probably reflects the truncation problem; that is, many successful patent applications made in recent years are not yet granted patents. Despite this problem, it is remarkable that the figure indicates an increase in the number of patents with assignees in the United States since the end of the 1990s, reflecting that R&D networks have been rapidly established among universities, companies, and public institutes in the United States. Successful patent applications by organizations in Europe have remained low.

Through the intensive R&D activities on lead-free solders, Japanese companies led the way in commercializing electronic products based utilizing lead-free solders. Table 15 lists some of the lead-free electronic products for mass production by manufacturing companies in Japan as well as Europe and the United States (Handwerker, Gayle, de Kluizenaar, and Suganuma, 2004; Suganuma, 2002).

Table 15 Development of Electronic Products Utilizing Lead-Free Solders for Mass Production by Manufacturing Firms in Japan, Europe, and the United States

Company	Year	Electronic Product
Matsushita Electric Industry (Japan)	1998	Compact MD player
	1999	VCR
	2000	Compact cassette player
NEC (Japan)	1998	Pager
	1999	Notebook computer
Hitachi (Japan)	1999	VCR, Freezer, Cleaner
	2000	Washing machine, Air conditioner
	2000	Notebook computer
Sony (Japan)	2000	VCR
	2000	TV, Notebook computer, Desktop computer
Toshiba (Japan)	2001	Notebook computer
Ericsson (Europe)	2001	Cell phones
Motorola (US)	2002	Cell phones

The first mass-produced product incorporating lead-free solders in the world was the compact MD player released by Matsushita Electric Industry in the fall of 1998. The company began the mass production of VCRs at the end of 1999. The process of lead-free soldering had become fourth generation and had been expanded for other products including cassette players by the middle of 2000 and is currently used in the overseas manufacturing of the company. NEC started to use lead-free solders in producing pagers at the end of 1998. The company introduced its lead-free notebook computers in October 1999 and is currently applying lead-free solders to other types of

PC. Hitachi has been actively promoting the transition to lead-free solders since 1999 and announced that approximately half of the products it produces in Japan incorporated lead-free solders in the middle of 2000. Sony completed its adoption of lead-free solders in camcorders in March 2000 and has begun to make a similar changeover in its overseas manufacturing of TVs as well. Toshiba had started to utilize lead-free solders in manufacturing many products by the end of 2000. Other, smaller manufacturers are rapidly catching up with these first movers in developing and commercializing electronic products incorporating lead-free solders (Suga, 2002; Suganuma, 2000).

On the other hand, commercialization of electronic products was delayed in Europe and the United States. Ericsson released cell phones incorporating lead-free solders in 2001 and Motorola in 2002. Although large companies such as Philips and Siemens were achieving implementation of lead-free soldering in Europe, there was no pan-European industry forum involving (SMEs) until recently. One of the important issues which still remain in Europe is that there are many SMEs which are seriously lacking awareness and technology support, with implementation concerns on such issues as inventories, re-training, rework, reliability, and labeling not yet addressed clearly (Nimmo, 2003).

4. Conclusion

In this paper we examined how university-industry collaboration networks are formed and function for the creation of innovation. The case of lead-free solders was analyzed, by looking at technological development and public policies for the regulation of lead. Network analysis was conducted on data on the memberships of research and development projects and consortia as well as scientific papers related to lead-free soldering technologies. Although the scope of our research conducted here is rather limited and the analysis is preliminary, this study illustrates that university researchers could play an essential role in establishing research and development networks among academia, industry, and the public sector for promoting technological and institutional changes.

Proposals to regulate the use of lead for soldering in products including electronic equipment were initially made in the United States. While the proposed legislations were not enacted in the end, the move to develop lead-free soldering technologies was started at the industrial level in Japan, with the initiative of university professors to set up a working group on lead-free solders within an academic society. Since then, several research and development projects were established, later with financial support from the public sector, involving not only large manufacturers of consumer electronic products but also small firms producing materials and equipment for solders as well as universities and public research institutes. Through these projects technological development and evaluation were conducted cooperatively, with the formulation of roadmaps headed by university professors was particularly effective in coordinating the views and behavior of diverse actors, with clearly specified milestones towards the development of lead-free soldering technologies. The establishment of extensive collaboration networks in Japan, linking academia, industry, and the public sector, was critical in promoting innovation on lead-free solders.

In the United States, on the other hand, while legislative move toward regulating the use of lead was made earlier than in other regions, the formation of networks between universities, companies, and public institutes did not proceed quickly as discussions on regulation ceased, although the U.S. networks have been growing rapidly, with several public institutes centrally positioned along with large electronic companies. Compared with Japan and the United States, the formation of networks in Europe has been delayed. While there are several European universities which have been very active in conducting scientific research on lead-free solders, the European networks have been created with universities and companies positioned in separate parts of the networks, which could have contributed to inhibiting close collaboration between university and industry for the development of lead-free solders. One of the reasons of delayed or immature formation of networks in Europe and the Untied States could be that universities researchers in Europe and the United States did not play the critical role of taking the initiative, at least at an early stage of technological development, to create networks linking academic researchers, public institutes, and companies producing materials and equipment in industry for cooperation and coordination for technological evaluation and standardization.

While university has recently been under strong pressure to contribute to economic growth with technology transfer to industry through patent applications and licensing as well as establishment of start-up companies, this case suggests that there are other important channels through which university could make beneficial contributions from societal perspectives. In cases where social issues such as the protection of public health, safety, and the environment are involved, the role of university would be particularly valuable in establishing and maintaining close networks incorporating relevant actors with diverse interests and backgrounds for the evaluation, verification, and standardization of emerging new technologies from a relatively neutral position. This role of providing social functions through networks should not be ignored in discussing the promotion of university-industry collaboration.

The concept of national innovation systems has been proposed and used to examine the peculiar ways in which innovation is conducted in each country. Although this concept has been very useful in guiding discussions on various differences in practice and performance between countries, common methodologies have not yet been established, which have discouraged quantitative empirical studies for international comparative studies. This study illustrated a possibility of applying quantitative as well as visualization methods of social network analysis to examining the structure of networks of university-industry collaboration within national innovation systems. Although the analysis of this study is limited to the cases of the United States, Europe, and Japan, a broader comparative study would generate interesting findings on similarities and differences between countries in terms of the formation and performance of university-industry collaboration networks for bringing forth innovation.

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