Area Development and Policy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rard20

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To cite this article: Sohyun Park & Yangmi Koo (2021) Impact of proximity on knowledge network formation: the case of the Korean steel industry, Area Development and Policy, 6:2, 181-199, DOI: 10.1080/23792949.2020.1797518

To link to this article: https://doi.org/10.1080/23792949.2020.1797518

AREA DEVELOPMENT AND POLICY
2021, VOL. 6, NO. 2
https://doi.org/10.1080/23792949.2020.1797518

Regional Studies Association

RESEARCH ARTICLE

Impact of proximity on knowledge network formation: the case of the Korean steel industry

Sohyun Park [a] and Yangmi Koo [b]

ABSTRACT
Empirical research shows that the relationship between proximity and knowledge cooperation assumes a linear or an inverted 'U' shape. This study of knowledge networks in the South Korean steel industry shows that the relationship may assume other forms. Cognitive, organizational and geographical proximity all play crucial roles in explaining the knowledge network. In the case of cognitive and geographical proximity, the relationship is linear, while in the case of organizational proximity, the relationship is wave-like, reflecting the distinctive characteristics of the country's steel industry, which is hierarchically led by several large conglomerates.

ARTICLE HISTORY
Received 4 September 2019; Accepted 14 July 2020

KEYWORDS
proximity, knowledge network, inverted 'U'-shaped relationship, patent data, social network analysis, steel industry

摘要
邻近性对知识网络形成的影响：以韩国钢铁业为例。*Area Development and Policy*. 实证研究表明，邻近性与知识合作之间的关系呈线性或倒U形。本文对韩国钢铁业知识网络进行了研究，研究表明，这种关系也有可能呈现出其他形式。无论是认知、组织还是地理位置的接近，都对知识网络的构建起着至关重要的作用。在认知和地理接近的情况下，这种关系是呈线性的，而在组织接近的情况下，这种关系是呈波浪式的，这反映出韩国钢铁业的鲜明特点，该产业是由几家大型企业集团按等级划分领导地。

关键词
临近, 知识网络, 倒U型关系, 专利数据, 社会网络分析, 钢铁业

RESUMEN
Impacto de proximidad en la formación de redes del conocimiento: el caso de la industria de acero de Corea. *Area Development and Policy*. Las investigaciones empíricas demuestran que la relación entre la proximidad y la cooperación en materia de conocimiento adopta una forma lineal o de U invertida. Este estudio de las redes de conocimiento en la industria del acero en Corea del Sur muestra que la relación podría adoptar otras formas. Las proximidades cognitiva, organizativa y geográfica desempeñan funciones

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decisivas a la hora de explicar la red de conocimiento. En el caso de la proximidad cognitiva y geográfica, la relación es lineal, mientras que en el caso de la proximidad organizativa la relación es como una ola que refleja las características distintivas de la industria del acero en el país, dirigida de modo jerárquico por varios grandes conglomerados.

PALABRAS CLAVE
proximidad, red de conocimiento, relación en forma de U invertida, datos de patentes, análisis de redes sociales, industria del acero

АННОТАЦИЯ
Влияние близости на формирование сетей знаний: пример корейской сталелитейной промышленности. *Area Development and Policy*. Эмпирические исследования показывают, что связь между близостью и кооперацией знаний принимает линейную или перевернутую 'U'-образную форму. Настоящее исследование сетей знаний на примере южнокорейской сталелитейной промышленности показывает, что эти отношения могут принимать и другие формы. Когнитивная, организационная и географическая близость играют решающую роль в объяснении сетей знаний. В случае когнитивной и географической близости эта связь линейна, в то время как в случае организационной близости она волнообразна, отражая отличительные особенности сталелитейной промышленности страны, иерархически организованной в рамках нескольких крупных конгломератов.

КЛЮЧЕВЫЕ СЛОВА
близость, сеть знаний, инвертированные 'U'-образные отношения, патентные данные, анализ социальных сетей, сталелитейная промышленность

INTRODUCTION

The construction of knowledge networks among agents plays an important role in the absorption and creation of new knowledge and has been directly associated with economic performance since the mid-1980s (Boschma, 2005; Hagedoorn, 2002; Nooteboom et al., 2007). Policy-makers also have paid attention to the ways to facilitate developing cohesive knowledge networks at a regional or a national scale and to support innovation. In an attempt to understand the mechanism of knowledge network formation, several studies have focused on how several dimensions of proximity affect the choice of cooperation partners (Broekel & Boschma, 2012; Cantner & Meder, 2007; Cassi & Plunket, 2014; Heringa et al., 2014; Nooteboom et al., 2007; Uzzi, 1997). It comes as no surprise that proximate agents tend to collaborate. However, being 'too close' (Nooteboom et al., 2007) can offset the advantages of cooperation. In this regard, Boschma and Frenken (2010) indicated that an inverted 'U'-shaped relationship exists between proximity and cooperation. Several subsequent empirical studies checked for the existence of this inverted 'U'-shaped relationship in terms of different kinds of proximity, but their results varied. Mowery et al. (1998) and Nooteboom et al. (2007) revealed the existence of an inverted 'U'-shaped relationship with respect to cognitive proximity, whereas Broekel and Boschma (2012) and Heringa et al. (2014) identified a linear relationship.

Although the growing body of literature on proximity and its influence is abundant and diverse, two major limitations must be considered. First, most empirical studies dealt with fast-growing fields, such as bio-tech, nano-tech and electronic-tech, and focused on developed countries (Broekel & Boschma, 2012; Ter Wal, 2014). The lack of empirical research dealing with mature industries in developing countries or latecomer countries might lead to a biased understanding of the innovation process. Second, among dimensions of proximity, the concept of organizational proximity is fuzzy and has not been fully assessed empirically. While Boschma (2005) separately defined social, institutional and organizational proximity, these three dimensions overlap in terms of their theoretical definitions. Although a few empirical studies have examined this concept (Balland et al., 2016; Broekel & Boschma, 2012; Cassi & Plunket, 2010), definitions of proximity are slightly different, and variables remain in their simple forms.

To fill the research gaps, this paper sheds a light on the dynamic influence of technological, organizational and geographical proximity on knowledge network formation in the case of the South Korean steel industry from 1988 to 2013. In particular, by exploring organizational proximity in terms of interorganizational relations, gradual proximate variables are developed considering several forms of organizational configuration. The relationship between various forms of proximity and choice of cooperation partner is then examined by constructing a logistic regression-quadratic assignment procedure (LR-QAP) model using co-patent data. By doing so, the study aims to understand the underlying mechanisms of knowledge network formation and to reveal the possibility of the existence of alternative relationship types between proximity and collaboration.

The paper is organized as follows. The literature on proximities and interorganizational relation is reviewed in the next section, and organizational proximity is defined. The third section provides a brief history of the Korean steel industry. The fourth section illustrates the procedures of collecting patent data and agent information as well as constructing the two models. The results are discussed in the fifth section. The sixth section concludes and draws conclusions for future research.

RELATIONSHIP BETWEEN PROXIMITY AND KNOWLEDGE NETWORK FORMATION

Several studies have defined various dimensions of proximity based on the fundamental assumption that actors coordinate across each form of proximity in order to find the most efficient distance for facilitating innovation while avoiding the risk of lock-in or knowledge leakage. Boschma (2005) proposed five dimensions of proximity, namely cognitive, geographical, organizational, social and institutional proximity. Cognitive and geographical proximity are well defined and have been verified in diverse ways with tangible and countable variables such as Standard Industrial Classification (SIC) code, International Patent Classification (IPC) code and physical kilometre distance (Broekel & Boschma, 2012; Koo & Park, 2012). However, the other three dimensions theoretically overlap, and ways of measuring these dimensions have not been fully developed.

This section provides an overview of theoretical viewpoints and empirical studies which use the concept of proximity to understand the underlying mechanisms of knowledge network formation. After reviewing cognitive, geographical and organizational proximity, it is suggested that the literature on interorganizational relations provides valuable insights for resolving the fuzziness of the concept of organizational proximity. Studies of the inverted 'U'-curve relationship between proximity and likelihood of collaboration are also examined.

Three dimensions of proximity

Cognitive proximity refers to the extent to which actors share a common knowledge base. Similarity in knowledge cognition enhances absorptive capacity, which in turn enables an actor to verify, interpret and exploit novel knowledge provided by others at a low cost. There is a tradeoff between cognitive proximity and distance, because too much of the former can impede learning and innovation because derivative ideas, unexpected spillovers and technological lock-in can occur when cognitive proximity is high (Boschma, 2005; Nooteboom, 2000).

Geographical proximity, which has long been argued to be a facilitator of knowledge diffusion, is associated with spatial distance between two actors (Jaffe, 1989). High geographical proximity implies low transaction costs and a high possibility of transfer of tacit knowledge through face-to-face contact. As several forms of proximity are introduced in the literature, however, the complementary effect of geographical proximity on other proximities has also been verified. Breschi and Lissoni (2003) showed that geographical proximity loses its predictability when social proximity is included as a control variable. Ponds et al. (2007) argued that geographical proximity can be substituted for institutional proximity, because the former exerts positive effects on cooperation between a company and research institutions, whereas institutional proximity alone does not lead to cooperation. These studies indicate that geographical proximity should not be overemphasized, but it should be understood in association with other different types of proximity.

Organizational proximity was initially proposed by Torre and Rallet (2005) to explain the interdependent relationship between two different actors, namely similarity logic and adherence logic. Later, Boschma (2005) diversified the concept to consider three types of logic: organizational, social and institutional. The latter two concepts were defined as a trust relationship based on common institutions, corresponding to the similarity logic of Torre and Rallet (2005), and the former, which was developed from adherence logic, was defined as 'relations shared in an organizational arrangement, either within or between organizations' (Boschma, 2005, p. 65). While the concepts seem straightforward, empirical studies based on Boschma's (2005) formulation employ different labels for the same idea or a broader term incorporating one or two discrete proximities (Table 1). For example, first, former affiliation and former collaboration experience are most frequently applied to measure organizational or social proximity, interchangeably (e.g., Balland et al., 2016; Broekel & Boschma, 2012; Cassi & Plunket, 2010). However, these two variables are not sufficiently able to reflect diverse forms of interdependency or organizational arrangements. Rather, these proxies partially describe different forms of organizational interaction. Second, the form of organization that measures whether the organizations are the same firms, research institutes and universities, or not, is often defined as institutional proximity (e.g., Broekel & Boschma, 2012; Cassi & Plunket, 2010). While the variable is an effective proxy to measure similarity in organizational routine and incentive system, it is not a good reflection of interorganizational relations. Third, whether any two actors have collaborated and the forms of organization are or are not the

Table 1. Studies related to organizational proximity.

	Theoretical studies		**Empirical studies**			
	Torre and Rallet (2005)	Boschma (2005)	Cassi and Plunket (2010)	Broekel and Boschma (2012)	Broekel and Boschma (2012)	Balland et al. (2016)
Concept/ variable	Adherence logic	Organizational proximity	Former cooperation		Affiliation	Affiliation
	Similarity logic	Social proximity		Former affiliation	Former cooperation	
		Institutional proximity	Organization form		Organization form	

same are often incorporated into prediction models as dichotomous variables in the form of 0 and 1 (e.g., Broekel & Boschma, 2012; Heringa et al., 2014). Due to the operationalization problem, it is not possible to examine linear or non-linear relationships between organizational proximity and the likelihood of collaboration. In order to deal with these limitations, the aspects of organizational proximity require expansion. As diverse interorganizational relationships are becoming more prevalent throughout the value chain, there is a need to construct detailed variables in a more systematic way.

The literature on interorganizational relations should mitigate these research gaps regarding the measurement of organizational proximity. The literature on interorganizational relations sheds a light on the dynamic relationships between diverse organizations (Dicken & Thrift, 1992; Yeung, 1994, 2008). Yeung (2008) separated the relationships along the scale from market to hierarchy, including affiliation, joint venture, supply–demand, cooperation in marketing or research and development (R&D), non-profit cooperation and ethnic/personal network. Organizational proximity could be classified and measured based on an ordinal scale from autonomy to control using Yeung's categorization. In this study, it is hypothesized that each level of organizational proximity may affect network formation differently. Higher organizational proximity can facilitate collaborations among actors by reducing uncertainty and opportunism and by entailing similar norms and incentive schemes (Cassi & Plunket, 2014). Yet, high proximity is not necessarily positively associated with technological collaboration because some forms of organizational relationships such as joint ventures are intended to facilitate market entry rather than collaborative research.

Inverted 'U'-shaped relationship between proximity and the likelihood of collaboration

While proximity is generally known as a strong facilitator of collaboration, excessive proximity can be detrimental for effective learning and can hamper the likelihood of collaboration because of the increased possibility of overlap, leakage and so on (Nooteboom et al., 2007). To put the premise another way, if the degree of proximity and the likelihood of collaboration exhibits an inverted 'U'-curve relationship, there can be an optimal distance between actors yielding successful collaboration and optimal performance by balancing learning and variety. This relationship can inform the development of an innovation strategy at an organization level, and an industrial policy can be very different depending on this relationship. For example, if there is a linear relationship with geographical proximity, spatial policy such as industrial park development is effective in facilitating collaborative learning. In the opposite case where geographical proximity exhibits a non-linear relationship, policy-makers need to devise sophisticated incentives to promote collaboration in consideration of the dynamics of proximity rather than focusing on spatial policy. In this regard, several empirical studies have been conducted to discover whether the effects of proximity on tie formation are either linear or an inverted 'U'-shaped relationship. Most of them have dealt with cognitive proximity (Boschma & Frenken, 2010; Mowery et al., 1998; Nooteboom et al., 2007). Empirical research shows somewhat different results, depending on socioeconomic contexts in space and time (Boschma, 2005). Mowery et al. (1998) and Nooteboom et al. (2007) found that there is an inverted 'U'-shaped relationship between technological proximity and mutual learning and innovation between firms. Meanwhile, Cantner and Meder (2007) found a linear relationship between technological proximity and selection of cooperative partners based on German patent data. In Heringa et al. (2014), all forms of proximity among actors, including geographical, technological, organizational and social, were shown to have a linear influence on innovation, publication, sales, cooperation and idea-sharing among actors in the Dutch water sector. Broekel and Boschma (2012) examined the impacts of four forms of proximity – cognitive, organizational, social and geographical – on the probability of technical cooperation among Dutch airline industry firms. They tested for the existence of an inverted 'U'-shaped relationship between geographical proximity and technical proximity and found no evidence to support this hypothesis. There are possible explanations for the seemingly contradictory findings. First, the evidence indicates an inverted 'U'-relationship for exploration-type knowledge, but a linear relationship for exploitation-type knowledge (Cassi & Plunket, 2014; Nooteboom et al., 2007). Exploration-type knowledge different from the existing knowledge base is more likely to require collaboration with less proximate actors. In line with the difference in knowledge type, second, there can be an inverted 'U'-relationship for an industry whose development is accelerating and a linear relationship for a mature industry. A new industry often emerges combining different fields of knowledge and can be more diverse in terms of organization and geography than a mature industry. Third, spatial scale matters. Especially in national level studies, actors are all relatively proximate so an inverted 'U'-relationship may not be found (Heringa et al., 2014).

All these studies share the underlying assumption that there are only two possible forms of relationship, linear or inverted 'U'-shaped relations. However, it is possible that other forms exist as well. For example, in the defence industry or the nuclear power industry, which both involve small, exclusive research groups, high proximity is crucial and there would be no room for a moderate level of proximity. In the case of an oligopoly, the relationship can be controlled by a small number of lead firms, rather than following linear or inverted 'U'-shaped relationships.

STEEL INDUSTRY IN SOUTH KOREA

The steel industry in South Korea has grown dramatically during the past 50 years. As of 2016, Korean steel production was 68.6 million tons, or 4.3% of world production, making Korea the sixth largest steel producer in the world (Korea Iron & Steel Association, n.d.). In the mid-2000s the industry underwent a major transformation in terms of technology, organization and geography. It became technically broader, organizationally integrated and more flexible, as well as becoming geographically decentralized and capable of employing a multi-location strategy (Park, 2016).

Industrial policies of South Korea in the 1960s and 1970s involved selective promotions of particular sectors with artificial allocation of resources by national government (Koo, 2013). With a shifting focus to heavy and high value-added industries from light industries, the steel industry in South Korea was strategically promoted by the government from the late 1960s. The rise of the Korean steel industry was particularly led by the growth of the Pohang Iron and Steel Company (POSCO), a state-owned corporation. In 1970, POSCO built an integrated steel mill in Pohang city with the assistance of a loan from Japan and technical consultation with Nippon Steel (Song, 2002). The 'Steel Industry Promotion Law' of 1970 also granted POSCO benefits in terms of taxation, infrastructure and protection (Amsden, 1989). Along with the Heavy and Chemical Industrialization Programme (1973–79), the steel industry contributed to the growth of industrial clusters in the southeastern part of the Korean peninsula (Shin & Ciccantell, 2009). While the industry relied on adopting imported technologies up until the early 1980s when POSCO constructed the second mill in Gwangyang city, POSCO pursued internal technological development from the late 1980s. POSCO established the Pohang University of Science and Technology (POSTECH) in 1986 and the Research Institute of Industrial Science and Technology (RIST) in 1987 to conduct fundamental research on product and process technologies (Song, 2002). This so-called tripartite in-house R&D system (POSCO-POSTECH-RIST) contributed to the development of innovative process-productivity increasing technologies such as mini-mills and strip-casting technologies (Won & Choi, 2003).

This government-led and POSCO-centric industry underwent industrial restructuring after the Asian financial crisis in 1997, which was wrapped up around 2004. In mediating the crisis, POSCO was privatized in 2002, and bankrupt companies were merged into or acquired by other companies. The abandonment of tariffs in 2004 resulted in an influx of imports of steel products from the United States, Japan and China. Environmental regulations on steel products were intensified. These domestic and international circumstances resulted in the following changes in technological, organizational and geographical aspects of the industry after 2004.

First, in terms of technology, production innovations and environmental protection increased in importance relative to steel-making process technologies. According to the IPC analysis of Park (2016), increasing numbers of patents relate to a variety of materials needed to meet the diverse needs of customers and expand shares in high-end markets. For example, intensive surface treatment of steel and high-strength transmutation steels were developed to meet the demands of the car manufacturing industry. At the same time, methods for water purification and slag recycling were developed as part of efforts to comply with international environmental protection agreements (Won & Choi, 2003), intensifying the need for steel companies to collaborate with other organizations such as research institutes and customers.

Second, organizationally, massive acquisitions in the domestic steel industry have modified the existing hierarchical structure centred only on POSCO. In particular, Hyundai Steel, an affiliate of Hyundai Motor Group, acquired Samyang Special Steel Co., a stainless steel manufacturer, in 2001. It also acquired Hanbo Steel in 2004 after Hanbo went bankrupt in 1997 due to a large investment in an integrated steel mill in Dangjin. As a result, the Hyundai group expanded its car manufacturing and construction business into the integrated steel industry. In a similar way to Hyundai steel, POSCO established a new subsidiary, POSCO Special Steel Co., when it took over Sammi Special Steel Co. in 1997. A result of restructuring was the emergence of an oligopolistic industry led by POSCO and Hyundai Steel. This consolidation was accompanied by a move to strengthen organizational flexibility. Diverse interorganizational relations, such as strategic alliances and joint ventures, have become more prevalent throughout the value chain (e.g., in terms of investment in resources, overseas expansion and technology development). This flexible organizational strategy was sustained even after the global financial crisis of 2007–08 and is comparable with the large-scale mergers and acquisitions in the western and Japanese steel sectors.

Third, the organizational restructuring catalysed the geographical decentralization of the industry. While heavy industries including the steel industry used to be concentrated in south-eastern coastal areas of the Korean peninsula, a new cluster was created in Dangjin city located in the middle of the west coast after Hyundai Steel acquired Hanbo Steel and completed construction of an integrated steel mill. Several steel-making companies such as Dongkuk Steel and Hankuk Steel constructed new factories in Dangjin following Hyundai Steel. As a result of the creation of a new cluster and acquisitions after the large-scale restructuring of 1997, most companies simultaneously operate several factories in multiple locations in Korea. Figure 1 shows the specialized regions and locations of major actors as of 2013.

DATA AND METHODS

Data collection and processing

Data collection and processing involved the identification and operationalization of an independent variable, several dependent variables and several control variables.

A co-patent data set was used in order to build a knowledge network (the dependent variable). Although the limitations of patent data remain an obvious challenge, it is an effective proxy for knowledge sharing and innovation in several aspects. After the late 1980s, internal technology development increased, along with R&D collaborations in the steel industry. Furthermore, Ejermo

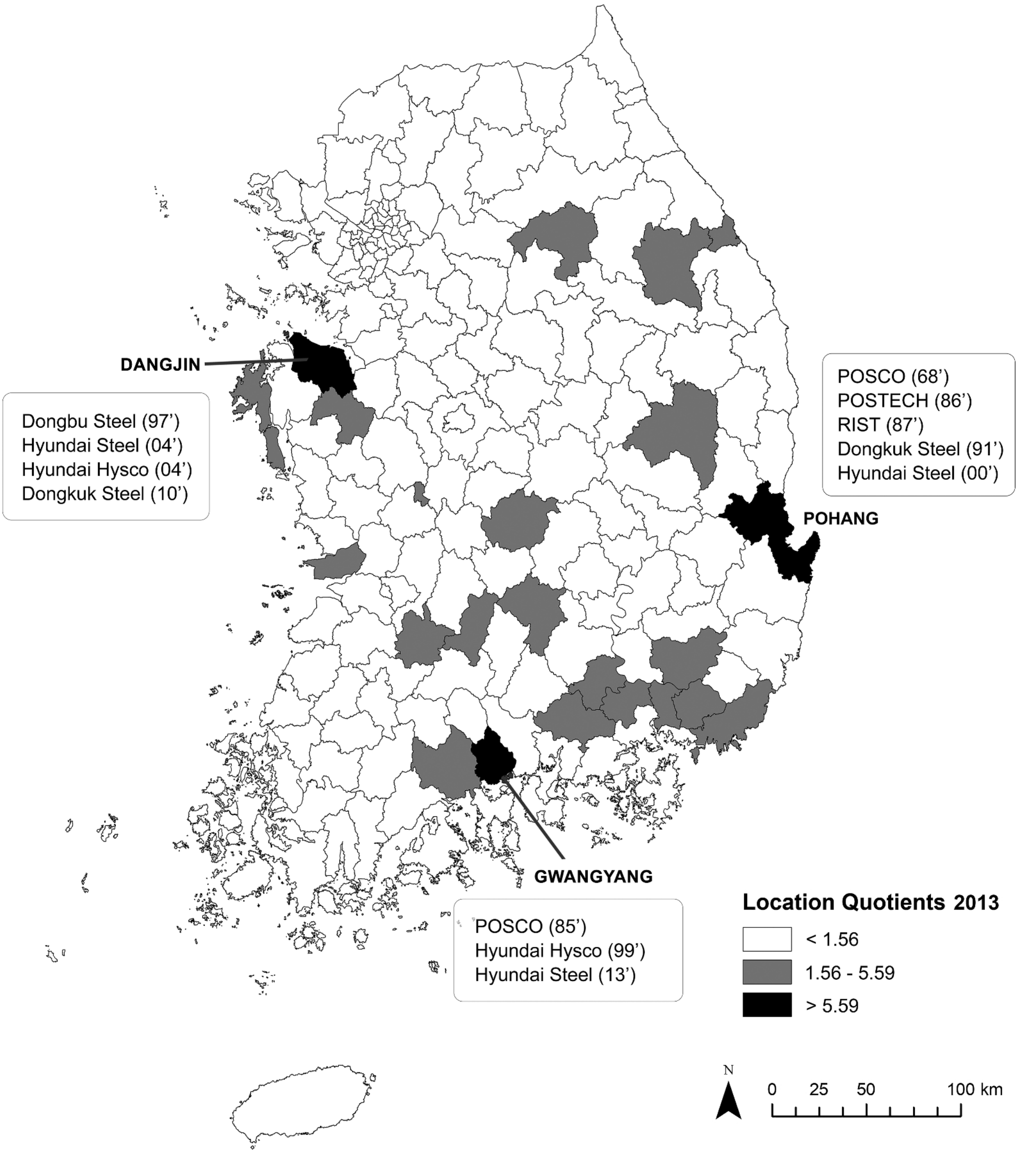

Figure 1. Location quotients of steel production and the multilocation strategy of major actors in the South Korean steel industry, 2013.

and Karlsson (2006) considered co-patent data a more appropriate proxy for knowledge transfer than patent citations because it is a planned result of choice and interaction.

The data set used to build a network consisted of all steel-related patent data between 1988 and 2013 obtained from the National Digital Science Library (NDSL). The data set was built by combining IPC extraction and a search strategy. IPC (B21, B22 and C21–C23) incorporate patents regarding processes of steel-making and associated machines. Meanwhile, searching for mid-processes and mid-products, such as hot rolling and steel sheet, enable extraction of patents regarding non-ferrous metal processing and specific products. A total of 14,701 patents were extracted. The total number of patents with at least one inventor reporting a

Korean postal address was 10,308. The final database including only co-patents comprised 1332 patents attributed to 296 distinct applicants. The applicants were organizations, including firms, universities and research institutes. Based on the data, South Korean steel industry knowledge networks were constructed for two periods, 1988–2003 (Figure 2) and 2004–13 (Figure 3).

As already mentioned, the South Korean steel industry was reorganized during the Asian financial crisis in the late 1990s. The restructuring process was to some extent completed in 2003. Therefore, by building two models, one can examine whether the knowledge-creation mechanism has changed after industrial restructuring. It was assumed that the impact of the global financial crisis of 2007–08 on steel industry R&D activities was not significant as the increasing rate of patent application was steady.

As explained above, the analysis aimed to assess the impact of various forms of proximity on the structure of the South Korean steel industry knowledge network. In particular, the model estimates the influence of the different types of proximities on the likelihood that two actors are linked. The dependent variable is dichotomous and indicates whether organization *i* applied for more than one patent with organization *j* in the given period. It was assumed that knowledge exchanges are always reciprocal in nature, thus indicating that network links are bidirectional.

As most actors are corporations and research institutions, the cognitive, organizational and geographical information about the applicants (the independent variables) was gathered from

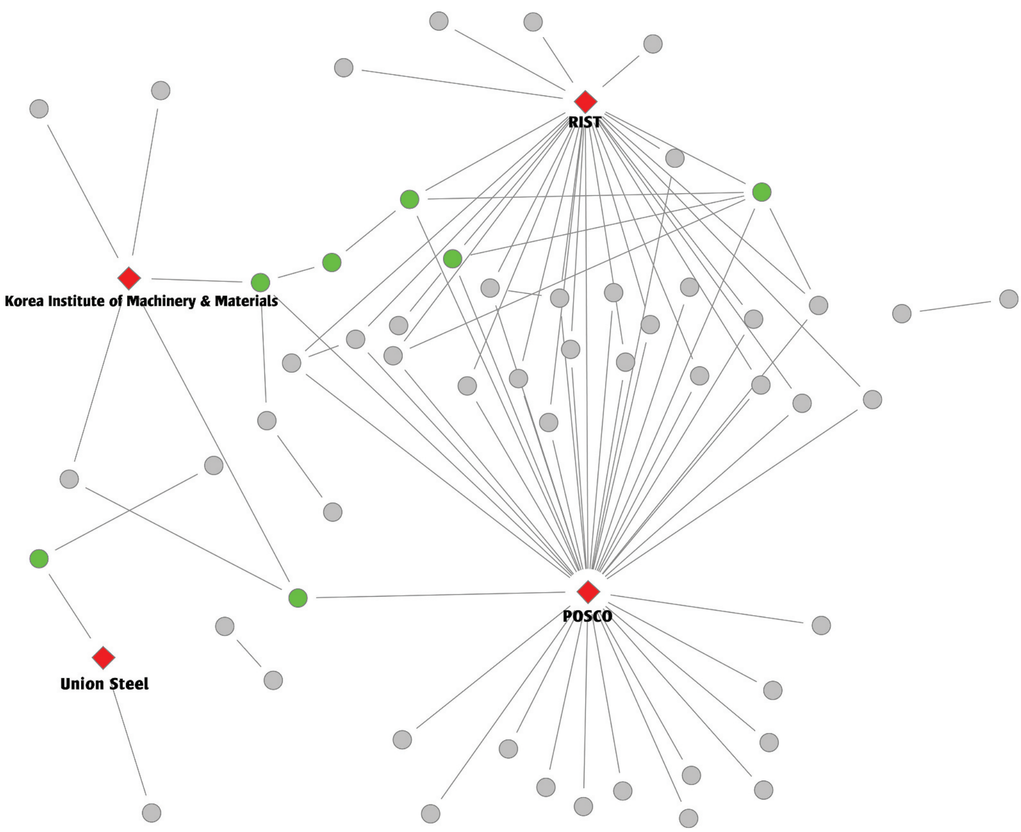

Figure 2. Cumulative knowledge network of the South Korean steel industry as of 2003.

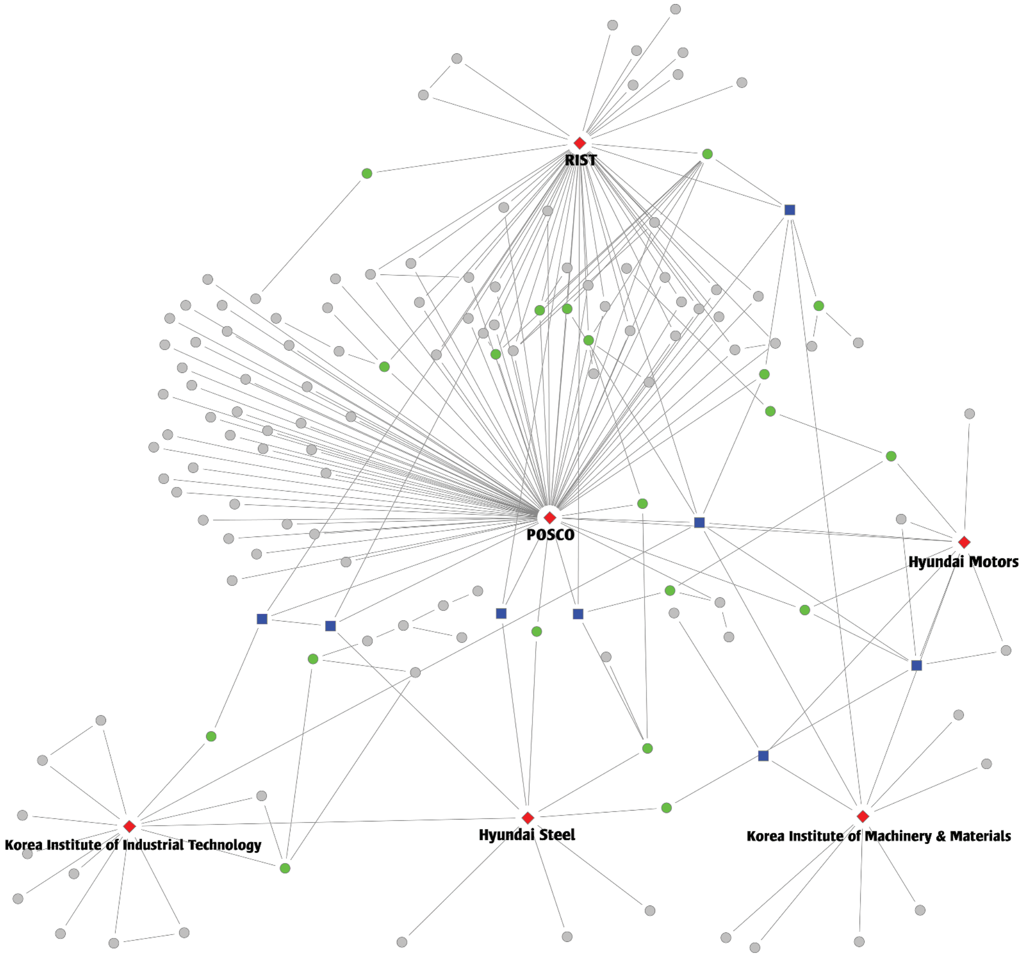

Figure 3. Cumulative knowledge network of the South Korean steel industry as of 2013.

formal document sources, such as the Korea Investors Service and the Financial Supervisory Service. A complete list of variables is included in Table 2. Table A1 in Appendix A in the supplemental data online shows the quadratic assignment procedure (QAP) correlations among these variables. Most variables turn out to be weakly correlated. Only the quadratic terms of cognitive proximity, as well as some interorganizational relation indicators, show considerable correlation with their non-squared counterparts:

- *Cognitive proximity*: refers to the technological similarity of the knowledge bases of two organizations. To measure cognitive proximity, the three-digit IPC assigned to each patent was used. According to Jaffe (1989) and Cassi and Plunket (2010), the variable *TECH* is defined based on the frequency of actors filing in the same IPC and is calculated using the trigonometric Cosine index. Given that the values of the Cosine index are between 0 and 1, the similarity index ranges from 0 and 1, with 1 indicating perfect technological similarity. In the estimations, a quadratic term ($TECH^2$) for the similarity indicators was also used to check for potential non-linear effects.

Table 2. Summary of variables

Variable	Description	Type	Average (2003)	Average (2013)
Dependent variable				
LINK	Co-patent	Dichotomous	0.06	0.02
Cognitive proximity				
TECH	Cosine index to measure similarity of International Patent Classification (IPC) code	Continuous	0.22	0.33
$TECH^2$	Test of non-linear relation in IPC code proximity	Continuous	0.06	0.04
Geographical proximity				
GEO	Log of Euclidean distance between two actors' main facilities	Continuous	12.37	11.27
GEO^2	Test of non-linear relation in geographical proximity	Continuous	5.74	2.59
Organizational proximity				
ORG-Group	affiliation	Dichotomous	0.02	0.01
ORG-Equity	equity (joint venture, equity investment, logistic cooperation, etc.)	Dichotomous	0.04	0.02
ORG-Nonequity	non-equity (spinoff, work experience, etc.)	Dichotomous	0.04	0.01
ORG-Mediated	lock-in (whether A and B has IOR with the same another actor)	Dichotomous	0.13	0.04
Control variables				
Patent-size	Difference of the number of patent	Continuous	243.95	127.21
Org-form	Similarity of organizational form	Dichotomous	0.31	0.29

- *Geographical proximity*: to assess the effect of geographical proximity, the geographical distance (km) between two organizations was calculated (*GEO*), resulting in a continuous positive variable. Given that the process of creating new knowledge occurs in the factory of a steel industry organization, the minimum distance (km) between factories was calculated. A squared term to control for non-linear effects (GEO^2) was estimated.
- *Organizational proximity*: interorganizational relations are divided into ordinal scales, from autonomy to control, according to 'relations shared in an organizational arrangement' (Boschma, 2005, p. 65) and to relationships along the scale from market to hierarchy (Yeung, 2008). If two actors are completely independent, the proximity is very low; conversely, organizational proximity is very high if they are part of the same hierarchical system. In previous studies, the interorganizational relationship variables have not been parameterized when examining the inverted 'U'-relationship due to the nature of discrete data. Exceptionally, Heringa et al. (2014) tested the inverted 'U'-relationship of organizational proximity, but the study parameterized the difference in each actor's organizational characteristics, which is closer to being a measure of the similarity of attributes rather than a measure of the proximity in relations. In this paper, four metrics were defined according to the degree of proximity – same affiliation, equity relationship, non-equity relationship and mediated relationship from higher to lower in proximity – in order to verify the existence of an inverted 'U'-relationship.
- *Affiliation (ORG-Group)*: being affiliated in the same business group is the most hierarchical and proximate type of relationship among IORs. Specifically, conglomerates generally operate a common research centre in a business group. For example, Hyundai Steel has a joint laboratory with other affiliates, including Hyundai Motors and Kia Motors. POSCO also owns and governs RIST and POSTECH. The variable *ORG-Group* was defined as 1 if two actors *i* and *j* belong to the same business group.
- *Equity relationship (ORG-Equity)*: as one of the middle forms between hierarchy and market relations, an equity relationship is a relatively explicit relation that interlocks two actors' profits and losses in the form of a joint venture or equity investment. The variable *ORG-Equity* was defined as 1 if actor *i* has an equity relationship with actor *j*.
- *Non-equity relationship (ORG-Nonequity)*: as one of the middle forms between hierarchy and market relations, a non-equity relationship is relatively less explicit than an equity-based relationship and does not involve share capital. It includes spinoffs, work experience and various agreements such as memoranda of understanding (MOU). The variable *ORG-Nonequity* was defined as 1 if actor *i* has a non-equity relationship with actor *j*.
- *Mediated relationship (ORG-Mediated)*: if actors B and C separately form an equity or non-equity relationship with actor A, A could profit from the structural hole between B and C. Some studies have argued that the structural hole might increase the cognitive proximity between B and C, leading to triadic closure (e.g., Ter Wal, 2014). However, in the Korean steel industry, which is highly conglomerate-centric and exclusive, the actors who have IOR with major companies could be caught in a lock-in situation. Nonetheless, the actors who do not have a strong interorganizational relationship with a certain actor may potentially form diverse ties. The variable *ORG-Mediated* was defined as 1 if the union of the equity and non-equity relationship sets for actor *i* intersects with that of actor *j*.

Several control variables that might affect the likelihood of being linked in the technological knowledge network were included. First, the logarithm of the difference in the number of patent applications (*Patent-size*) was computed as a control for variations in the inventing behaviour of organizations. Given that the organizations in this sample were heterogeneous, the study employed controls for the fact that motives to create novel knowledge and cooperate with others can vary based on the forms of the organizations involved, including listed conglomerates, unlisted conglomerates, small-to-medium enterprises, research institutes and universities. More precisely, the variable (*Org-form*) indicates two organizations having the same form of organization.

Data analysis

The data analysis involved testing for the impact of the dimensions of proximities on the likelihood that two actors collaborate in technological innovation. A network regression model was constructed to verify the relationships. Among the four network-modelling techniques suggested by Broekel et al. (2014), the LR-QAP was adopted. LR-QAP is a logistic regression that can be used to test for correlation between multiple network relationships. It is capable of handling the control autocorrelation problem by applying the QAP. QAP can handle inherent non-independent observations of network data using random permutations of the matrix rows and columns (Marijtje et al., 2011). According to the empirical research of Walsh (1994), the results of LR-QAP are more conservative than those of traditional logistic regression. In addition, the interpretation of coefficients is intuitive, as in the case of traditional logistic regression (Borgatti et al., 2013). To control for multicollinearity, the residual permutation method proposed by Dekker et al. (2007) was implemented. The software UCINET 4.0 was used to process the data.

RESULTS AND DISCUSSION

The regression results for the technological knowledge network for the 1988–2003 period are summarized in Table 3, and the results for the 2004–13 period are shown in Table 4. A more sophisticated model should be constructed if the coefficients are not statistically significant. However, as the purpose of this study was to examine the influences of the variables and their temporal changes, the final model was selected. Slight differences exist in the magnitudes of the coefficients between the models with and without multicollinear variables.

Table 3. Results of the logistic regression-quadratic assignment procedure (LR-QAP) network regression (1988–2003)

ID		Coefficient	Odds ratio	*T*	*p*	*P*(ge)	*P*(le)
(Intercept)		–1.611	0.200	–1.188			
cog	*TECH*	5.894***	362.775	6.378	0.001	0.001	1.000
	TECH^2	–8.606	0.000	–24.429	0.146	0.855	0.146
geo	*GEO*	–0.274*	0.760	–2.495	0.063	0.938	0.063
	GEO^2	–0.028	0.973	–1.020	0.361	0.640	0.361
org	*ORG-Group*	2.928***	18.695	4.430	0.002	0.002	0.999
	ORG-Equity	1.005*	2.731	2.169	0.055	0.055	0.946
	ORG-Nonequity	1.112	3.041	2.114	0.110	0.110	0.891
	ORG-Mediated	–4.022***	0.018	–1118	0.004	0.997	0.004
control	*Patent-size*	0.001**	1.001	8.807	0.027	0.027	0.974
	Org-form	–0.855	0.425	–1.897	0.188	0.813	0.188

Notes: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.
Log-likelihood (LL) = –115.013; R^2 = 0.449; p = 0.001.

Table 4. Results of the logistic regression-quadratic assignment procedure (LR-QAP) network regression (2004–13)

ID		Coefficient	Odds ratio	T	p	P(ge)	P(le)
(Intercept)		–2.348	0.096	–3.619			
cog	*TECH*	4.324***	75.460	6.998	0.004	0.004	0.997
	TECH^2	–0.597	0.551	–0.561	0.441	0.560	0.441
geo	*GEO*	–0.290**	0.748	–5.168	0.027	0.974	0.027
	GEO^2	–0.012	0.988	–0.667	0.552	0.449	0.552
org	*ORG-Group*	2.999***	20.069	11.684	0.001	0.001	1.000
	ORG-Equity	0.523	1.687	1.882	0.211	0.211	0.790
	ORG-Nonequity	1.612***	5.012	5.851	0.008	0.008	0.993
	ORG-Mediated	–4.959**	0.007	–1416.480	0.022	0.979	0.022
control	*Patent-size*	0.001***	1.001	20.594	0.007	0.007	0.994
	Org-form	–1.039***	0.354	–5.149	0.008	0.993	0.008

Notes: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.
Log-likelihood (LL) = 744.491; $R^2 = 0.237$; $p = 0.001$.

The values of R^2 for the 1988–2003 and 2004–13 periods are 0.449 and 0.270, respectively, which demonstrates that the model performs well in terms of explanatory power. Yet, the fact that the explanatory power of the model decreases over time reflects increased uncertainty regarding the form of the relationship. Overall, the findings confirm the theoretical predictions: all types of proximity have an impact on the likelihood of one actor being linked to another actor. Furthermore, as time passes, the signs do not change, even though the values of the coefficient in the two models change, thus revealing robustness.

More specifically, cognitive proximity has high explanatory power in both models. The positive influence of IPC code proximity was lower in 2013 compared with 2003. This difference reflects the increase in technological diversity in the steel industry. However, as a result of verifying the inverted 'U'-relationship, the squared term ($TECH^2$)is not significant in both periods. Considering the high correlation of cognitive proximity and the likelihood of being linked, the existence of an inverted-'U'-shaped relationship cannot be confirmed. This result corresponds to those of Cantner and Meder (2007) and Heringa et al. (2014), who identified a linear relationship. It is because technological development and patent applications in mature industries such as the steel industry are more focused on narrow specific technological areas rather than the exploration in a wide range of technological areas. Therefore, the stronger cognitive proximity and the closer technology distance, the higher the probability of network connectivity. The linear relationship in cognitive proximity reflects the fact that industrial structure of the Korean steel industry has been centred on a few large companies and powerful research institutions such as POSCO, Hyundai Steels and RIST. These central actors can cover a wide range of knowledge bases, so they can occupy technologically close positions with a diverse group of collaborative partners.

Geographical distance has a strong and negative effect on the likelihood of link formation between two actors in both periods (i.e., between 1988–2003 and 2004–13). Even when technological and organizational variables are controlled for, geographical proximity remains significant. While this finding confirms that geography matters, it may also be partly influenced by the fact that central actors in this industry open several branches and are able to interact with local actors in various places with the help of multilocation strategy. A test for the significance of an inverted 'U'-shaped relationship between the likelihood of an actor being linked with others and geographical proximity was not significant, and so this relationship was deemed to be linear.

With respect to organizational proximity, the four variables related to interorganizational relations show different impacts. First, the fact that organizations belong to the same business group had a positive effect on the likelihood of cooperation in both study periods. A relatively high coefficient indicates that a hierarchical interorganizational relationship has a strong influence on link formation in the steel industry. In the case of *ORG-Equity*, the effect was significant in the 1988–2003 period, but the coefficient decreased and became insignificant in the 2004–13 period. On the contrary, *ORG-Nonequity* had a positive influence, and its *p*-value decreased in the 2004–13 period. Over time, the influence of the non-equity networks, which have no explicit control over one another, became greater. Tests for correlation of *ORG-Nonequity* with other variables (see Table A1 in Appendix A in the supplemental data online) revealed that the actors in non-equity relations became proximate in terms of both technology and geography in 2013. For innovation non-equity relations with proximate actors might be preferable to equity relations over time, with a policy of supporting strategic alliances between conglomerates and small-to-medium enterprises contributing to collaborative learning (Bae et al., 2005). The *ORG-Mediated* variable had a negative effect on the likelihood to cooperate in both periods, and its intensity became stronger in the 2004–13 period. Two different organizations linked with the same actor are highly unlikely to interact with each other in the technical knowledge sector, despite indirect linkages. This result contrasts with the triadic closure argument suggested by Ter Wal (2014). In other words, although actor diversity has increased with time, active interactions between actors have become insignificant owing to exclusive connections centred on a few central actors such as POSCO and RIST and the consequent establishment of a low-density hierarchical network. Even though organizational changes which can be expected eventually to alleviate the highly hierarchical structure of the market environment have occurred, evidence of the existence of strong ties is weak (Rowley et al., 2000), and power asymmetry remains (Grabher, 1993).

Figure 4 reports the differing values of the coefficients for different indicators of the degree of organizational proximity in the models for the two time periods. The lines connecting the four values show an upward zigzag path to the right.

These results permit conceptualization of the relationship between proximity and the likelihood of link formation as shown in Figure 5. The relationships with cognitive and geographical proximity are linear, whereas the relationship with organizational proximity is wave-like relationship. If there is a direct relationship in any form from the organizational point of view, the probability of linkage formation increases. However, when a non-equity relationship exists, the positive influence on link formation increases, whereas an equity relationship has a smaller influence and its impact is insignificant. The left-hand section of the wave-like relationship is similar to the inverted 'U'-shaped relationship that has been observed for cognitive proximity in the existing literature given that the influence of the equity network is reduced compared to that of non-equity network. However, if two actors belong to the same enterprise group, in which case organizational proximity reaches its highest level, the probability of cooperation increases further. That is, if organizational proximity is very high, the probability of forming a linkage increases. Therefore, the relationship assumes a wavy shape, that is, the probability first increases, then decreases, and then increases again.

CONCLUSIONS

The research reported in this paper tested for the existence of an inverted 'U'-shaped relationship between proximity and the likelihood of cooperation with respect to several kinds of

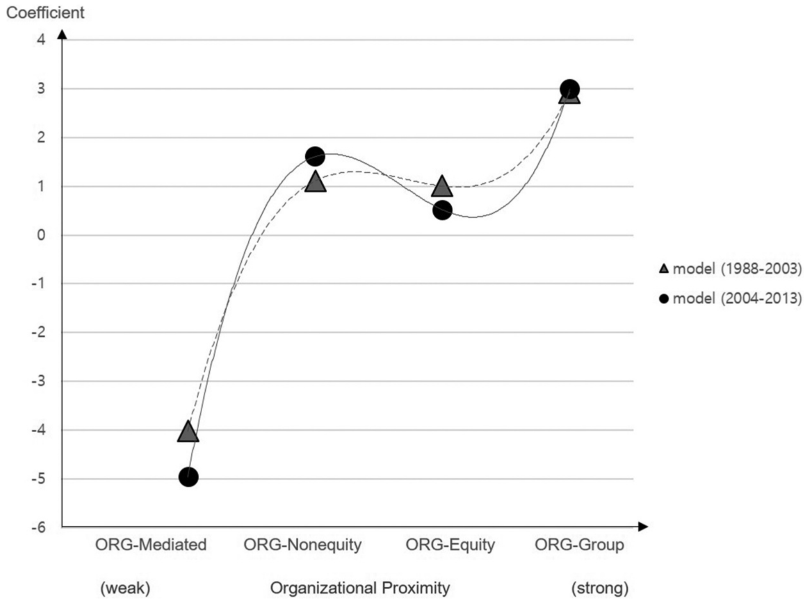

Figure 4. Coefficients of organizational proximity in models for the two periods.

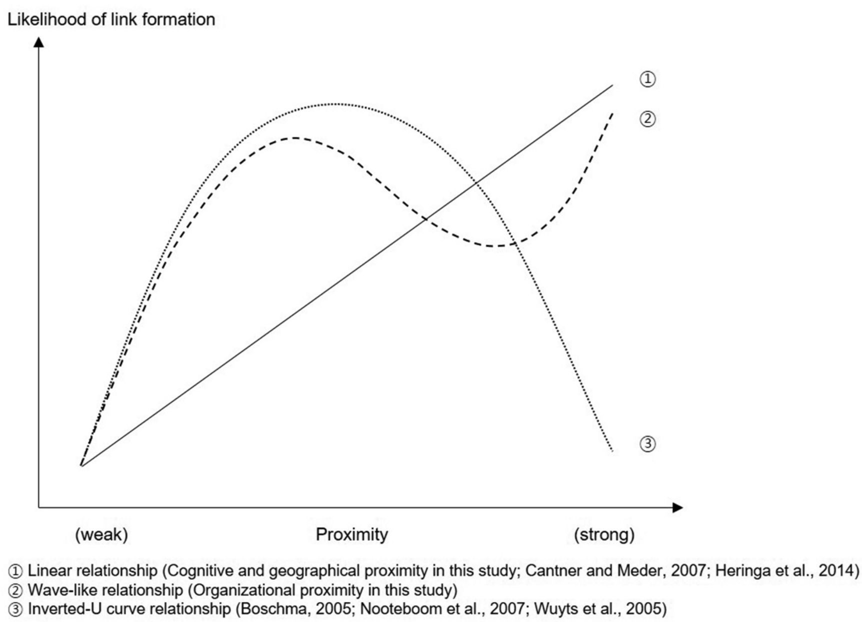

Figure 5. Relationship between proximity and knowledge network formation.

proximities by taking the Korean steel industry as a case. Proximity is required to make connections in knowledge networks, but it does not necessarily have a positive influence on technological collaboration. Patent data associated with the steel industry in South Korea were collected, and an LR-QAP model was employed to test for relationships in the case of three forms of proximity (cognitive, geographical and organizational) that might have an impact on network formation.

The analyses indicated that different forms of proximity do act as drivers of knowledge network formation. Cognitive, geographical and organizational proximity among organizations increase their likelihood to connect and exchange knowledge with other organizations in a network. Most interestingly, geographical proximity was found to be a driver of network formation, even when controlling for other proximities. Empirical evidence pointed to the existence of a linear relationship between proximity and collaboration likelihood in the case of cognitive and geographical proximity. A wave-shaped relationship was identified in the case of organizational proximity. These findings reflect the distinctive characteristics of the Korean steel industry, which is hierarchically led by several conglomerates. It is generally accepted that proactive government industrial policy for R&D collaboration promoted knowledge network formation in Korea. Similarly, a lot of industry–industry or industry–academic collaborative projects mediated by national or regional research funds were identified in the Korean steel industry. However, this kind of cooperation is mainly centred on the link between central actors and small firms, so the links among small firms appear to be weak. Therefore, government industrial and technological policies should more focus on the promotion of a network among peripheral small actors.

As for recommendations, further research concerning the effect of proximity on firms' innovation performance is required. The analysis reported in this paper indicates that cognitive and geographical proximity and some degree of organizational proximity contributed to network formation in the form of co-patent development. Yet, one cannot conclude that co-patents depending on proximity might yield innovative performance and economic benefit. Future work is required to explore this issue.

Finally, there is a need for more dynamic analyses which can account for knowledge network formation over time. These analyses can examine two aspects, namely how the dynamics of the network is affected by the various proximities, and how these proximities change over time due to the evolution of networks. Examination of these and other questions is crucial for gaining a better understanding of the causes and consequences of knowledge network dynamics in space. They can also contribute to further progress in the study of network formation.

ACKNOWLEDGEMENTS

The authors thank the editors, Professor Sam Ock Park and Professor Michael Dunford, for important feedback and editorial help, and the anonymous referees for their valuable comments.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

FUNDING

This work was supported by the 4-Zero Land Space Creation Group funded by the Ministry of Education and National Research Foundation of Korea.

SUPPLEMENTARY MATERIAL

Supplemental data for this article can be accessed here.

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