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Managing Complexity of Technological Knowledge: Diversity, Convergence, and Dynamism

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Abstract

Managing Complexity of Technological Knowledge: Diversity, Convergence, and Dynamism

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In order to create constant innovation, management of technological knowledge, where the data and information related to R&D are transformed into creative knowledge, has been increasingly emphasized. Moreover, as the complexity of recent technological knowledge continues to increase, there is a growing demand for more systematic management considering complexity to obtain novel insights about rising managerial problems and solutions. Technological knowledge no longer includes a single technology but various related technologies and disciplines, and various technologies converge into a new technology. In addition, as the people who use technological knowledge become more diversified and its ripple effects become more widespread, technological knowledge is exposed to a more dynamic environment.

Therefore, this dissertation aims to examine the characteristics that constitute the complexity of technological knowledge, and resolve major managerial problems resulting from its characteristics. Specifically, this study defines the emerging characteristics that accelerate the complexity of technological knowledge as diversity, convergence, and dynamism; then three research questions related to each characteristic are addressed through three

research themes. Each research theme is studied by utilizing and creatively combining appropriate methodologies to answer each research question.

The first study focuses on the research theme for managing diversity in complexity, and deals with the identification of intellectual structure of technological knowledge. Recently, technological knowledge has a multidisciplinary nature. Hence, it is important to understand the knowledge structure and research trends in order to develop the direction of R&D strategy. In this study, a framework that includes journal citation network and network analysis is proposed as a method to identify the structure of multidisciplinary technological knowledge. Specifically, a journal citation network is constructed; then network centrality measures and brokerage analysis are used to explore the intellectual structure of nanoscience and nanotechnology, where multidisciplinary research is actively done. The proposed approach can provide a microscopic and macroscopic view of the multidisciplinary structure of technological knowledge by identifying the important technology element regarding knowledge flow, and the intermediary role of each knowledge source regarding knowledge exchange.

The second study focuses on the research theme for managing convergence in complexity, and deals with the prediction of technological convergence. As technological knowledge is rapidly evolving and new technologies are being created through convergence, the boundaries between technologies are blurred and it becomes more difficult to predict new technology trends. In this study, a framework that includes patent co-classification analysis and link prediction is proposed as a method to predict the technological convergence of emerging technologies. The proposed approach has the advantage in that it can discover the potential convergence, even if it does not exist in the past, because it predicts the potential link based on the characteristics of the network. The proposed approach is applied to 3D printing technology, and it is expected to be utilized in various technologies and industries in the future.

Finally, the third study focuses on the research theme for managing dynamism in complexity, and deals with the evaluation of technology-intensive and large-scale projects. Increasingly, technology investment projects face a dynamic environment that incorporates both macroscopic system and microscopic individuals. In this study, a new approach to dynamic feasibility analysis for investment projects is proposed through an integrated simulation model using system dynamics (SD) and agent-based modeling (ABM). The combination of SD and ABM is suggested due to their complementary strengths. The former SD part elucidates the relationships among system elements that constitute project's benefits and costs, while the latter ABM part depicts users' emergent behavior with their heterogeneity. A case study demonstrates the applicability of the proposed approach. The findings show that the proposed approach can provide a valuable and flexible framework for analyzing project feasibility in a dynamic environment.

Keywords: Technological knowledge; Complexity management; Diversity; Convergence; Dynamism; Network analysis; Link prediction; System dynamics; Agent-based modeling

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Chapter 1

Introduction

1.1 Background and Motivation

In recent years, companies have faced the increasing speed of changes in markets, competitors, regulations, products, and technologies (Díaz-Díaz et al., 2008). To survive under this circumstance, continuous improvement of competitive advantage through innovation is a necessity (Danneels, 2002; Cefis and Marsili, 2005; Branzei and Vertinsky, 2006). In this regard, management of technological knowledge, where the data and information related to R&D are transformed into creative knowledge, has been increasingly emphasized as a core activity to create and maintain competitive advantage (Miller and Shamsie, 1996; Grant, 1996; Nonaka et al., 2000; Díaz-Díaz et al., 2008). Furthermore, as the complexity of recent technological knowledge continues to increase, the systematic management considering complexity is now indispensable for obtaining novel insights about rising managerial problems and solutions.

The phenomenon where the complexity of technological knowledge is accelerated can be explained by the emerging characteristics of technological knowledge. One reason for the increasing complexity is that technological knowledge includes various related technologies and disciplines rather than a single technology. Knowledge itself has fluidity and changing nature (Alexander et al., 1991). Kimbell (2001) explained that “the boundaries of knowledge and even what counts as knowledge are constantly changing.” The extent to which those characteristics appear in technological knowledge is increasing. Second, more and more new technologies emerge and evolve between fields of knowledge rather than within a single discipline (Song et al., 2017). Hence, the areas of knowledge are interrelated, and one area can influence or be influence by the others (Scheffler, 1999; Gibson, 2008). Third, technological knowledge is exposed to a more dynamic environment as the ripple effects of technological knowledge and the participants become more widespread. The ripple effects of technology investment projects span not only the specific technology investment area but also external areas such as economic, social, and environmental (El-Sayegh, 2008; Katrin and Stefan, 2011). Also, the participants have a substantial impact on an investment project because they create a demand that significantly affects the feasibility of the project.

Such characteristics of technological knowledge lead to significant managerial issues. First, it becomes more difficult to identify knowledge structures and research trends because of the multidisciplinary nature of technological knowledge. Second, it is difficult to predict new technology trends when the existing boundaries between technologies become blurred. Lastly, it becomes more difficult to evaluate the feasibility of a technology-intensive and large-scale project because it is exposed to a dynamic environment. This dissertation focuses on those problems arising due to the emerging complexity of technological knowledge.

1.2 Purpose

The overall purpose of this dissertation is to examine the characteristics of technological knowledge in terms of complexity, and further resolve the managerial issues resulting from its characteristics, and consequently provide useful insights and appropriate methods for managing complexity. Specifically, this dissertation is aimed at answering following questions.

1) How can knowledge structure be identified when related technologies and disciplines are diverse?
2) How can technology trend be predicted when technologies actively converge?
3) How can technology-intensive and large-scale project be evaluated when environments dynamically change?

Each question is addressed through three research themes, each of which related with emerging characteristics of technological knowledge. The detailed objectives of research themes are as follows.

The first theme deals with the following question: how can knowledge structure be identified when related technologies and disciplines are diverse? To identify the structure of multidisciplinary technological knowledge, this study suggests a framework where journal citation network and network analysis are used. Specifically, network centrality measures and brokerage analysis are used to explore the intellectual structure of a multidisciplinary field based on the journal citation network.

The second theme addresses the following question: how can technology trend be predicted when technologies actively converge? To predict the technological convergence of emerging technologies, this study proposes a framework where patent co-classification analysis and link prediction are used.

Finally, the third theme answers the following question: how can technology-intensive and large-scale project be evaluated when environments dynamically change? This theme suggests a new approach to dynamic feasibility analysis for technology investment projects. For a dynamic feasibility analysis, an integrated simulation model using system dynamics (SD) and agent-based modeling (ABM) is proposed due to their complementary strengths.

1.3 Scope and framework

This dissertation defines three emerging characteristics that accelerate the complexity of technological knowledge as *diversity, convergence*, and *dynamism*. Those terms are used to indicate the following situations faced by technological knowledge, particularly with regard to growing complexity.

1) *Diversity*: it refers to the condition of being composed of various related technologies and disciplines
2) *Convergence*: it refers to the condition of being merged into a new technology resulting in a blurring of existing boundaries between two or more areas of technology
3) *Dynamism*: it refers to the condition of being exposed to a dynamic environment with a range of potential effects and participants

Each aspect can cause significant managerial problems, and three of them are addressed in this research. Then three management issues related to each characteristic is transformed into research themes as shown in Figure 1-1.

The research themes derived from the previous process are as follows: (1) Identification of intellectual structure of multidisciplinary fields; (2) Prediction of technological convergence in emerging fields; and (3) Evaluation of feasibility of a technology project considering dynamic environments. Each theme is effectively addressed in this research by employing and creatively combining appropriate methods.

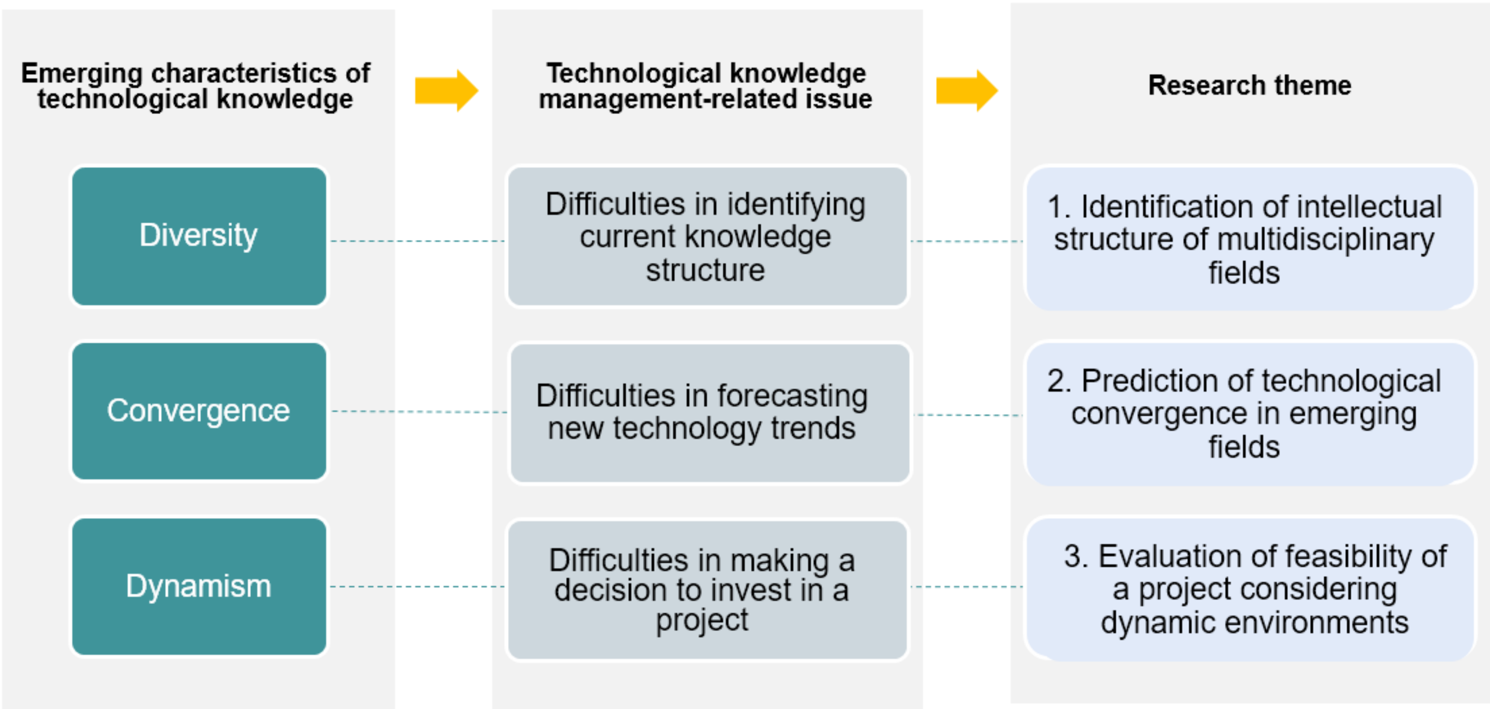

Figure 1-1 Scope and framework of this dissertation

1.4 Outline

This dissertation is composed of six chapters as shown in Figure 1-2. The remainder of this dissertation is organized as follows. Chapter 2 provides background of this dissertation by reviewing the concept of complexity, complexity management, and dimensions of complexity in technological knowledge. Chapter 3, 4, and 5 are main bodies of this dissertation. As explained in the framework of this dissertation, three research themes derived from the three aspects (i.e. diversity, convergence, and dynamism) are covered in these chapters respectively. According to the purpose of the theme, a suitable method is suggested with an illustration using empirical data.

Specifically, Chapter 3 addresses the research theme for managing diversity in complexity, and attempts to resolve the difficulties in identifying current knowledge structure. This study identifies the intellectual structure of a multidisciplinary field by using network centrality and brokerage analysis, and academic data. To investigate the intellectual structure of multidisciplinary field, the journal citation data is used to construct a knowledge source network because citation reflects direct influence between journals, which are knowledge sources, and thus can be considered as the knowledge transfer. Based on the knowledge source network, brokerage analysis is adopted along with centrality analysis because centrality measures can provide the information about important nodes in the knowledge network while brokerage measures can capture the specific role of nodes.

Chapter 4 focuses on the research theme for managing convergence in complexity, and deals with difficulties in forecasting new technology trends. The aim of this study is to predict technological convergence in emerging fields. For this study, patent co-classification data is used to forecast technological convergence because it is regarded as an indicator of technological connections. The data is transformed into a network form and then analyzed using link prediction method. Link prediction method is adopted due to its ability to estimate the likelihood of the existence of a link between two nodes in the future based on observed links and the attributes of nodes.

Chapter 5 addresses the research theme for managing dynamism in complexity, and resolves the difficulties in making a decision to invest in a project exposed to a dynamic environment. This study is aimed at providing a new method for feasibility study of a technology project considering dynamic environments. To incorporate a dynamics of macroscopic system and microscopic individuals, a combined system dynamics (SD) and agent-based modeling (ABM) is suggested. Specifically, the benefits and costs incurred by the project can be modeled as a SD model while the interactions of users who participate in the project can be modeled with an AB model. In addition, a SD model and an AB model should be combined because the behavior and interactions of users affect the overall system of benefits and costs, and vice versa. The project data of technology-intensive and large-scale project is used to illustrate the model's practical use.

Finally, this dissertation ends with conclusions in Chapter 6. This chapter presents the summary and contributions, and proposes future works.

	Chapter 1. Introduction		
	Chapter 2. Research Background		
	Chapter 3. Managing Diversity in Complexity	Chapter 4. Managing Convergence in Complexity	Chapter 5. Managing Dynamism in Complexity
Purpose	Identification of intellectual structure of multidisciplinary fields	Prediction of technological convergence in emerging fields	Evaluation of feasibility of a project considering dynamic environments
Data	Academic data: multidisciplinary research field	Patent data: emerging technology	Project data: technology-intensive, large-scale project
	Why?: academic data can represent knowledge structure of research fields; particularly, a journal citation reflects direct influence between knowledge sources, and thus can be considered as the knowledge transfer	Why?: patent data is an ample source for technical and commercial knowledge; specifically, patent co-classification has been regarded as an indicator of technological connections	Why?: project data contains guidelines for feasibility study, including associated cost, resulting benefits, their diverse elements, and causal relationships
Method	Network centrality analysis; Network brokerage analysis	Patent co-classification analysis; Link prediction	System dynamics (SD); Agent-based modeling (ABM)
	Why?: centrality measures can provide the information about important nodes in the knowledge network while brokerage measures can capture the specific role of nodes	Why?: link prediction can estimate the likelihood of the existence of a link between two nodes in the future based on observed links and the attributes of nodes when the network is constructed	Why?: combined SD and ABM can incorporate a dynamics of both macroscopic system and microscopic individuals
	Chapter 6. Conclusion		

Figure 1-2 Overall structure of this dissertation

Chapter 2

Research Background

2.1 Theoretical Background

2.1.1 Concept of Complexity

As Pigagaite et al. (2013) showed that there are "at least 31 definitions of complexity," there are many different interpretations of complexity depending on different domains of knowledge. Although no standardized definition of complexity exits, complexity generally indicates that there are many interrelated parts, patterns, aspects, data, concepts or elements, and consequently it is difficult to fully understand or cope with (Miyazaki and Kijima, 2000). The term complexity is often used for many aspects that we do not fully understand or manage (Botchkarev and Finnigan, 2015). In addition, complexity is explained by comparison with other concepts occasionally. For instance, the phenomenon of complexity can be differentiated from the concept of simplification as shown in Table 2-1 (Olmedo, 2010). Specifically, complexity paradigm is characterized as an opened system composed of interconnected agents with environment, disequilibrium, nonlinearity, and irreversibility. Moreover, complexity is distinguished from complicatedness: "Complicated systems have a large number of components with well-defined relations and roles, which are linear and fixed along time. Complex systems have usually a large number of components with non-linear relations and roles that evolve along time" (Olmedo, 2010).

Table 2-1 Comparison of simplification and complexity paradigm

	Simplification paradigm	**Complexity paradigm**
Openness	Systems are considered isolated structures	Systems are composed of agents interconnected and connected with environment
Equilibrium	Systems are considered structures in equilibrium	Systems are considered structures far from equilibrium
Linearity	The whole is approximately the sum of constituting parts	The whole is more than the sum of constituting parts
Reversibility	Time is exogenous and external to the system	Time is endogenous and internal to the system

2.1.2 Complexity Management

Since complexity is manifested in various areas of technology management and pertains to the business performance of companies, plenty of studies have been conducted on complexity management. In particular, research on complexity management has been actively carried out in the area of project management, new product/process development, and operations management.

Although each study presents a unique way to manage complexity, the prior strategies for managing complexity can be categorized into three types: (1) acquisition and evaluation of complex system; (2) reduction of complexity; and (3) control of complexity. As a fundamental step in complexity management, some studies focused on the acquisition and evaluation of complex system. For example, matrix-based approaches were suggested for the acquisition of system linkages and the evaluation of complex structures in product design (Lindemann et al., 2009). Meanwhile, many studies addressed approaches for the reduction of complexity in product/process management and operations management, including variety reduction program (Galsworth, 1994), modular product designs (Baldwin and Clark, 1997), and cellular manufacturing (Suresh and Kay, 1998). Perona and Miragliotta (2004) suggested two kinds of levers that can reduce complexity in operations system: complexity reduction levers, which reduce complexity at a physical level, and complexity management levers, which reduce the impact of a certain amount of physical complexity on system's performances. On the other hand, several authors mentioned that an increase in complexity can be an important strategy of successful complexity management (Lindemann et al., 2009). According to them, a specific level of complexity can allow the flexibility of process, and thereby provide competitive advantages (Maurer and Lindemann, 2007).

Nevertheless, managing complexity has been considered as a process of decomposition and encapsulation in many studies. Decomposition into several components that constitute complexity can reduce the perceived complexity, and also make complexity easy to manage (Botchkarev and Finnigan, 2015). Therefore, there are diverse frameworks of complexity dimensions across various research areas in management of technological knowledge. In this context, this dissertation decomposes the complexity into three aspects to effectively manage the complexity.

2.1.3 Dimension of Complexity

In order to systematically manage the complexity, complexity has been divided into various dimensions across various research areas. For example, in the area of project management, Hertogh and Westerveld (2010) developed six elements of complexity from the practitioners' view, including: technical, social, financial, legal, organizational, and time. In addition, they identified two types of complexity from the theoretical perspective: detail complexity, which indicates many components with a high degree of interrelatedness, and dynamic complexity, which describes the potential to evolve over time (i.e. co-evolution), and the limited understanding and predictability. Based on the Hertogh and Westerveld (2010)'s model, Dunović et al. (2014) suggested three parts in complexity: structural complexity, uncertainty, and constraints. Maylor et al. (2013) considered three dimensions of complexity: structural complexity, sociopolitical complexity, and emergent complexity. Botchkarev and Finnigan, (2015) suggested the complexity framework that identifies the types of complexity in the project. They categorized the complexity attributes into three system levels: external environment, project-internal environment, and product.

In the field of product management, the two dimensions of external and internal complexity received great attentions (Marti, 2007). External complexity arises from customer requirements, competitive forces, technological changes, etc. It makes companies broaden the range of product they have, and consequently increases the enterprise-internal complexity. Internal complexity indicates product complexity, organizational complexity, production complexity, etc.

In other fields of technology management, Perona and Miragliotta

(2004) developed a model of operations system complexity based on the empirical observations. The five dimensions in complexity for manufacturing or logistic systems are as follows: sale process, in & out logistics, new product development, production process, and process engineering. Miyazaki and Kijima (2000) defined two dimensions of complexity: external complexity (or uncertainty) and internal complexity, which refers to complexity related to the internal structure of the decision situation.

This dissertation defines diversity, convergence and dynamism as the dimensions of the accelerated complexity of technological knowledge, and conducts the research on each aspect.

2.2 Methodological Background

2.2.1 Network Metrics: Centrality and Brokerage

1) Centrality

Centrality, elaborated by Freeman (1979), is a measure that is widely used to find core nodes in networks and to quantify how important they are relative to others. There are several indices for centrality according to how we view a node as central. First, degree centrality measures how well connected each node is. In terms of degree centrality, a node that is linked with many other nodes is a central node. Degree centrality is simply defined as the number of links that a node possesses. Furthermore, this can be classified into in-degree and out-degree, that is, incoming and outgoing relations in a directed network (Wasserman and Faust 1994). Because the size of the network influences degree centrality, it is often standardized by dividing degree centrality by the maximum number of nodes that a node can be connected to, n-1, where n is the number of nodes in a network (Snijders and Borgatti 1999). Closeness centrality considers indirect ties that constitute a path by which a node can reach others. In terms of closeness centrality, a node that can reach other nodes through short distance paths is more central. Therefore, it is defined as the inverse of the farness of a node which is calculated by summing distances of a given node from all other nodes in a network. In a directed network, this can be differentiated in terms of in-closeness and out-closeness. In addition, standardized closeness centrality is calculated by multiplying n-1 to it. Betweenness centrality focuses on the extent that a node is positioned on the shortest path between other nodes in a network. That is, the more a node lies in the path between other nodes, the more central it is in terms of betweenness centrality. It is defined as the proportion of all shortest paths that include a given node. Furthermore, betweenness centrality can be standardized by dividing it by (n-1)(n-2) (Gould 1987).

2) Brokerage

Brokerage analysis is another way to understand a network by focusing on the intermediate relationships of nodes. It has been proposed and developed to explain the inconsistency between the real power and the centrality (Cook et al. 1983; Marsden 1983). Unlike centrality, it can be used to identify the specific role of each node in a network. Because of such benefit of brokerage analysis, it has been used in various areas such as building the national information and communication technology (ICT) frontier based on a patent citation network (Shin and Park 2007), investigating the multidisciplinary characteristics of technology management based on a journal citation network (Lee 2015), and studying the effects of brokerage roles on innovation performance based on a network of firms (Molina-Morales et al. 2016). Specifically, a broker is an intermediary actor who facilitates transactions between other actors who do not have direct connection (Gould and Fernandez 1989; Marsden 1982). Due to this strategic position in a network, a broker has the ability to enhance the knowledge transfer between actors who had been not directly and/or frequently connected so far (Batallas and Yassine 2006).

For brokerage analysis, there are three actors, where two of them are connected through the third, a broker. Assuming that a network is partitioned into mutually exclusive groups, brokers can be categorized into several types depending on the affiliations of three actors. Gould and Fernandez (1989) identified five different types of brokerage roles: (1) coordinator (w_I), (2) consultant (w_O), (3) gatekeeper (b_{OI}), (4) representative (b_{IO}), and (5) liaison (b_O) (see Figure 2-1. below, where node color indicates group affiliation).

(1) Coordinator: a broker mediates between the other two actors who belong to the same group of the broker.

(2) Consultant: a broker mediates between the other two actors who belong to the same group but not the group the broker belongs to.

(3) Gatekeeper: a broker mediates between the other two actors where the recipient actor and the broker belong to the same group.

(4) Representative: a broker mediates between the other two actors where the source actor and the broker belong to the same group.

(5) Liaison: a broker mediates between the other two actors where all three actors belong to different groups.

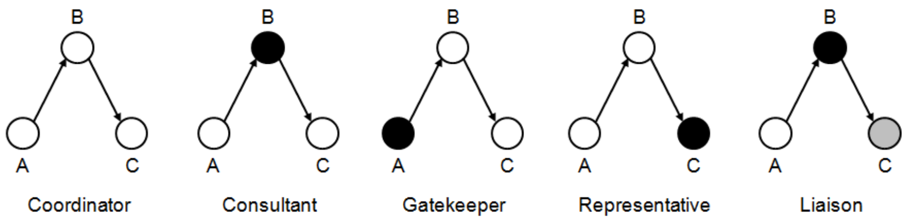

Figure 2-1 Five types of brokerage roles

When it comes to the journal citation network in this study, if all three journals belong to the same nano technology element, the journal that mediates between the other two journals can be called a coordinator. If a journal that links the other two journals that belong to the same nano technology element is affiliated with a different group from the other two, the intermediate journal can be named a consultant. These two brokerage types are within-group brokerages and thus they transfer the knowledge within the nano technology element. The next three types of broker are between-group brokerages. Depending to the group that the broker belongs to, they have different names. If a journal cited by the other journal from different technology element cites a journal that belongs to the same technology element, this journal delivers knowledge obtained from the technology element that it is affiliated with to the other technology element. Therefore, this journal is a representative in terms of knowledge flow. On the other hand, if a journal cites the other journal that belongs to the other technology element and cited by a journal from the same technology element, this journal is a gatekeeper in terms of knowledge flow. It delivers knowledge acquired from the other technology element to its technology element. When a journal connects two journals from different technology elements and it belongs to neither technology elements of two, it is a liaison. It transfers knowledge between two different technology elements as a third actor from the other technology element.

The formulas for brokerage indices according to the five types basically count the number of each type of brokerage roles. Specifically, a node j's coordinator score, w_{Ij}, is defined as follows:

$$w_{Ij} = \sum_{i=1}^{N}\sum_{k=1}^{N} w_I(ik) \quad ,(i \neq j \neq k),$$

where $w_I(ik)$ equals if ijk is true and if $m_i = m_j = m_k$, and 0 otherwise (here, m_j indicates the node j's group and N is the number of nodes in a network). Similarly, other types of brokerage scores are calculated. For a consultant score, w_{Oj}, $w_O(ik)$ is defined as 1 if $m_i = m_k \neq m_j$. For a gatekeeper score, b_{OIj}, $b_{OI}(ik)$ is defined as 1 if $m_i \neq m_j = m_k$. For a representative score, b_{IOj}, $b_{IO}(ik)$ is defined as 1 if $m_i = m_j \neq m_k$. For a liaison score, b_{Oj}, $b_O(ik)$ is defined as 1 if $m_i \neq m_j \neq m_k$. The total brokerage score of each node is the sum of its five brokerage scores. In addition, a partial score of each brokerage type can be obtained by dividing the raw scores by the number of two-step paths between i and k. Generally, to focus on the group relations rather than individual node's relations, partial scores are used (Hanneman and Riddle 2005).

2.2.2 Link Prediction

Link prediction is the fundamental link mining and analyzing tasks that tackle the problem of predicting the missing or unobserved links in current networks and promising or deleted links in future networks (Getoor and Diehl, 2005; Wang et al., 2015). Due to its predictive strengths, link prediction has been applied in various areas including: research collaborations (Sun et al., 2015), terrorists detection (Clauset et al., 2008), and patent partner recommendation (Wu et al., 2013).

Besides, many approaches and measures were suggested to solve the link prediction problem. For example, common neighbors (CN) is one of the most widely used measure in link prediction problem because of its simplicity. For two nodes, i and j, it is defined as the number of neighbors that i and j in common. Newman (2001) calculated this measure in the collaboration network and analyzed a correlation between this measure and the probability that they will collaborate in the future. Jaccard's coefficient (Jaccard) normalizes the size of CN by calculating the CN relative to total number of neighbors they have (Jaccard, 1901). Preferential attachment (PA) has gained attention for generating evolving networks (Barabási and Albert, 1999; Mitzenmacher, 2004). It simply calculates the product of the number of neighbors of i and j. Because PA can be calculated without the information of common neighbors, it has low computational complexity. Katz index (Katz, 1953) is defined as the sum of all paths, exponentially damped by length to give more weights to the shorter paths. Local path (LP) index (Lü et al., 2009; Zhou et al., 2009) is a measure that uses information of local paths with length two and three. LP is considered as a good measure since it provides competitively good prediction while requires lighter computation compared to the global path indices such as Katz (Lü et al., 2009).

Table 2-2 Example of network features for link prediction

Feature set	**Feature**	**Description**
Neighbor-based	Common neighbors	$\lvert\Gamma(i) \cap \Gamma(j)\rvert$
	Adamic/Adar	$\sum_{k\in\Gamma(i)\cap\Gamma(j)} \frac{1}{log\lvert\Gamma(k)\rvert}$
Path-based	Distance	Length of the shortest path between i and j
	Katz	$\sum_{l=1}^{\infty} \beta \cdot \ \lvert path_{i,j}^{<l>}\rvert$
Attribute-based	Interest similarity	Cosine similarity between the interests of i and j (i.e. cosine similarity between titles of author's publication)
	Preferential attachment	$\lvert\Gamma(i)\rvert \cdot \lvert\Gamma(j)\rvert$

By investigating various link prediction indices, the characteristics of a network can be detected based on the best-performing index because each prediction index incorporates network's features (Lü and Zhou, 2011; Sun et al., 2015). For example, as shown in Table 2-2, CN and Adamic/Adar are neighbor-based features, Distance and Katz are path-based features, and Interest similarity and Preferential attachment are attribute-based features (Sun et al., 2015). Most of the features have been studied in the prior research (Liben-Nowell and Kleinberg, 2007). The description of features follows the definition used by Liben-Nowell and Kleinberg (2007).

2.2.3 System Dynamics (SD) and Agent-based Modeling (ABM)

Although system dynamics (SD) and agent-based modeling (ABM) are the most important simulation methods that are available to understand complex systems (Phelan, 1999), they pursue totally different or competing viewpoints. (See the Appendix A for supplementary information about SD and ABM). SD models present a highly aggregated and feedback-rich view of the system using a deductive approach that understates behavior, whereas AB models present a highly disaggregated view of the system in which behavior emerges by using inductive reasoning to generate it (Martinez-Moyano et al., 2007). Lättilä et al. (2010) described the idea of contrasting the differences of the two modeling approaches based on the prior literature. SD has strength in that it can infer the emergence of a certain behavior because of the transparency of system behavior; however, it also has weakness in that the structure of simulation is fixed. On the other hand, ABM has strength in that it can model endogenous interactions of individual agents based on decision rules; however, it has weakness in that it is not suited to modeling macro system factors such as policy.

The different mechanisms of the two successful modeling approaches mean that they can have complementary roles and achieve an enhanced understanding of complex systems (Schieritz and Milling, 2003; Scholl, 2001). For example, Schieritz and Größler (2003) combined SD and ABM in order to simulate supply chains, because ABM is effective at modeling the evolution of individual interactions, such as creating new partnerships and discrete events that include mimicking certain types of action, whereas SD is useful to model ordering policies controlled by individual agents. Thus, a wide variety of views about combining the two modeling approaches are presented in prior literature (See the Appendix B for supplementary information about topics of the prior studies). The prior models that have integrated SD models and AB models can be categorized into three types according to the degree of, and direction of, interaction: (1) an independent model, which models the same problem through a SD model and an AB model respectively, and compares their simulation results; (2) a sequential model, which utilizes the partial schemes of an AB model as the input of a SD model, and vice versa; and (3) an interacting model, where the input and output of a SD model and an AB model are joined so that they alternate with each other (agents interacting with a single SD model and SD sub-models embedded in agents) (Vincenot et al., 2011).

Most of the attempts to combine a SD model and an AB model utilized SD to model a macroeconomic system and ABM to model processes that involve social interaction (Hines and House, 2001; Kieckhäfer et al., 2009; Martinez-Moyano et al., 2007; Schieritz and Milling, 2003). Similarly, it is appropriate to use an integrated approach that combines SD and ABM for the feasibility analysis of public sector investment projects in order to take into account the macroscopic system, where the benefits and costs incurred by the project are formed, and the microscopic interactions of users that affect the system. In other words, an integrated approach using SD and ABM has the ability to reflect the micro and macro changes that can vary depending on a particular situation, such as the implementation of a new policy after a project is underway. Specifically, the benefits and costs that occur can be modeled as a single SD model while the decision and interactions of users who participate in the project, and thus should be considered when evaluating project feasibility, can be modeled with an AB model. Furthermore, it is necessary to combine a SD model and an AB model because the behavior and interactions of users affect the overall system of benefits and costs, and vice versa.

Chapter 3

Managing Diversity in Complexity

3.1 Introduction

Technological knowledge no longer includes a single discipline/technology but various related disciplines and technologies. Nanoscience and nanotechnology (nano) fields are dynamic research areas where interdisciplinary research is actively done. Moreover, nano fields are promising research areas that are expected to deliver a great improvement in science, engineering, and medicine that may significantly influence our way-of-life (Roco and Bainbridge 2001, 2005). Because of such broad impacts, nano has attracted enormous interest from governments as well as researchers. This growing interest has led to an increase in investments in R&D for nano fields, along with an increase in the number of scientific publications and patent applications of nano fields (Huang et al. 2011).

To develop a direction of the international R&D and R&D strategies for nano, understanding the research trends of nano fields is indispensable and therefore, the investigation of an intellectual structure of nano fields is essential (Gorjiara and Baldock 2014). Hence, there have been many studies that attempt to discover nano fields' intellectual structure of interdisciplinary nature and most of them were based on bibliometrics. They mainly used publications and patents as a data source. Early studies usually count the number of publications and patents to search a trend of nano fields (Meyer and Persson 1998). Recently, many studies adopted the network perspective, where a set of nodes and links are defined as academic elements and bibliometric indicators of relationships, to understand the interdisciplinary structure of nano fields. Various forms of network were derived in prior studies depending on the choice of analysis elements and relationship indicators. Specifically, the nodes were defined using various academic units, including patent documents (Li et al. 2007; Chang et al. 2010), paper documents (Rafols and Meyer 2010; Takeda et al. 2009), journals (Leydesdorff and Zhou 2007; Leydesdorff 2007a, b; Larsen 2008), authors (Liu et al. 2014; Rueda et al. 2007), technology fields (Haung et al. 2004; Li et al. 2007), science fields (Porter and Youtie 2009; Rafols and Meyer 2010), institutions (Haung et al. 2004; Li et al. 2007; Liu et al. 2009), and countries/regions (Haung et al. 2004; Li et al. 2007; Larsen 2008; Zheng et al. 2014; Dang et al. 2010). The links among academic units were specified using common measures of bibliometrics, which are citation (Haung et al. 2004; Leydesdorff and Zhou 2007; Leydesdorff 2007a, b; Porter and Youtie 2009; Li et al. 2007; Liu et al. 2009), intercitation (Takeda et al. 2009), co-citation (Larsen 2008), bibliographic coupling (Rafols and Meyer 2010), and co-authorship (Larsen 2008; Liu et al. 2014; Rueda et al. 2007).

Among the diverse combination of nodes and links, the journal citation networks, where the nodes represent the academic journals and links are citation among journals, were frequently studied (Leydesdorff and Zhou 2007; Leydesdorff 2007a, b) because a journal citation network can provide a holistic view of academic fields in terms of knowledge structure. In addition, a journal citation network can be viewed as a kind of knowledge source network. While co-citation can describe similarity-based relationships, citation reflects direct influence between journals and thus, can be considered as the direction of knowledge transfer (King 1987). Based on the journal citation network, prior attempts investigated some network's structural characteristics, such as betweenness centrality, degree centrality, network size, network diameter, and average path length (Li et al. 2007; Larsen 2008; Rafols and Meyer 2010; Leydesdorff 2007a; Leydesdorff and Zhou 2007).

Although those prior studies contributed to understanding the intellectual structure of nano fields, they have a limitation in that they cannot detect the specific role of each node in the network of nano fields, because they focused only on the centrality measures. To deal with this limitation, this study aims to investigate the interdisciplinary characteristics of nano fields based on the journal citation network (i.e. knowledge source network), and further identify the journals that intermediate relationships between nano areas (i.e. technology elements) by using brokerage measures.

3.2 Knowledge Source Network

Recently, to visualize and investigate an intellectual and technological structure of nano field, a network analysis has been suggested and used in many studies, along with bibliometrics. Basically, a network consists of a set of nodes and links. Based on this fundamental format, various types of network can be constructed by varying the types of nodes and links. The types of nodes and links are selected depending on the purpose and focus of a research. The studies that used network analysis and bibliometrics together for investigating the field of nano had similar purposes in that they tried to present the knowledge structure of nano field and monitor the trends. However, the focus of the studies can be divided into two main aspects: technological/practical aspect and scientific/academic aspect. According to the focus of the study, the two main data sources for network analysis were patents and publications, respectively.

When it comes to the studies using patents, they examined the structure of technological knowledge in nano field by analyzing various network. The networks could have different levels through different types of nodes that represent analysis units such as patent documents, technology fields, institutions, and countries/regions. The links were built based on the relationships between the units such as citations, similarity of keywords, and collaboration. For instance, Li et al. (2007) used four levels of patent citation network to investigate the structure of nano field and to understand the knowledge transfer between patent documents, technology fields, institutions, and countries. They analyzed the network by using critical node, core network, and network topological analysis with some measures such as network size, average path length, and degree. Similarly, Hang et al. (2004) analyzed three levels of patent citation network, which are technology field, institution, and country. They discussed the structure of three networks and presented the knowledge flow patterns and key development trends of technology fields, institutions, and countries. Chang et al. (2010) used patent network analysis to monitor the technological trends in the field of Carbon nanotube field emission display (CNT-FED). They measured the technology centrality index and density index from the patent network, where the nodes are patents and the links are binary values calculated based on similarity between keyword vectors of patent documents. Dang et al., (2010) also investigated the trends in nano patents by analyzing the network of countries'/regions' patent offices. In their network, if two patent offices shared the published nanotechnology patent applications, the link between two existed. Zheng et al. (2014) examined collaboration in nano field by analyzing patent network, where the nodes are countries/regions and the links are collaboration between them.

On the other hand, the studies using papers as a data source for network analysis investigated the structure of academic knowledge in nano field. The networks were constructed at different levels by varying the types of nodes such as journals, science fields, paper documents, authors, institutions, and countries/regions. The links were added on the basis of bibliometric measures such as citations, co-citations, intercitations, and co-authorships. For instance, Leydesdorff (2007a), Leydesdorff and Zhou (2007), and Leydesdorff (2008a) provided a journal network of nano field based on the citation patterns among journals and measured the betweenness centrality as an index for interdisciplinarity to delineate interdisciplinary structure of nano field. Porter and Youtie (2009) used multi-tier networks of Science Citation Index (SCI)'s journal subject categories (SCs) in nano field to examine multidisciplinary nature of nano field. Similarly, Rafols and Meyer

(2010) constructed a network of SCs in bionanoscience fields based on the citation patterns between SCs to capture interdisciplinarity of the field. Furthermore, they built the network of articles linked by bibliographic coupling and then, they applied the concepts of diversity and network coherence. To measure the network coherence, they calculated mean linkage strength and mean path length from the network. Using paper documents as nodes, Takeda et al. (2009) also analyzed the (inter)citation network of papers to investigate the structure and research areas in nanobiotechnology. Focusing on the specific area of nano field, Larsen (2008) examined the knowledge structure in the field of nanostructured solar cell research by analyzing co-authorship network of countries/regions and co-citation network of journals. Liu et al. (2009) analyzed the citation network of papers at institution level and compared the structure and knowledge diffusion patterns in nano field in China, Russia, and India. In addition, Liu et al. (2014) used co-authorship network of researchers in nano field to investigate the structure and impact of research networking. The researcher network was measured by degree centrality, Bonacich Power centrality, structural holes, and betweenness centrality to capture the relative position of researchers. Rueda et al. (2007) also built co-authorship network of authors to study the collaboration network of nano field by focusing on the lead authors and co-authors contributing to the field.

In sum, prior studies conducted various network analyses based on the publications and patents data. Specifically, various levels of analysis entity, including paper/patent document, journal, author, technology/science field, institution, and country/region, and relationship information between entities, such as citation, co-citation, and co-authorship, were collected from the publications and patents data and represented as a network for further analysis.

Then they measured network's structural characteristics, such as degree centrality, betweenness centrality, and average path length, to understand the intellectual structure of nano field.

However, those centrality-based measures are unable to capture the specific role of each node in terms of the intermediate relationships between nodes. As a remedial measure, the brokerage analysis is applied to the nano journal network in this study. Although brokerage analysis has been used in many areas (Shin and Park 2007; Lee 2015; Molina-Morales et al. 2016), there has been no attempt to apply brokerage analysis to a nano journal network despite the fact that brokerage roles provide valuable information for understanding the structure of nano field.

3.3 Research Process

3.3.1 Overall Process

The overall process for identification of intellectual structure of nano field is shown in Figure 3-1. The process consists of four steps: data collection, technology element network analysis, knowledge source network analysis, and investigation of intellectual structure.

Firstly, the journals (i.e. knowledge sources) related to nano are defined and collected with their citation information. Also, the journals are assigned into relevant subarea based on the pre-defined classification scheme. Secondly, to analyze the technology element network, the nano subarea network is constructed, and centrality scores of subarea are measured. Thirdly, to investigate the knowledge source network, the nano journal network is constructed, and centrality scores and brokerage scores of journals are measured. Lastly, the intellectual structure of nano field is explored based on the technology element network and knowledge source network.

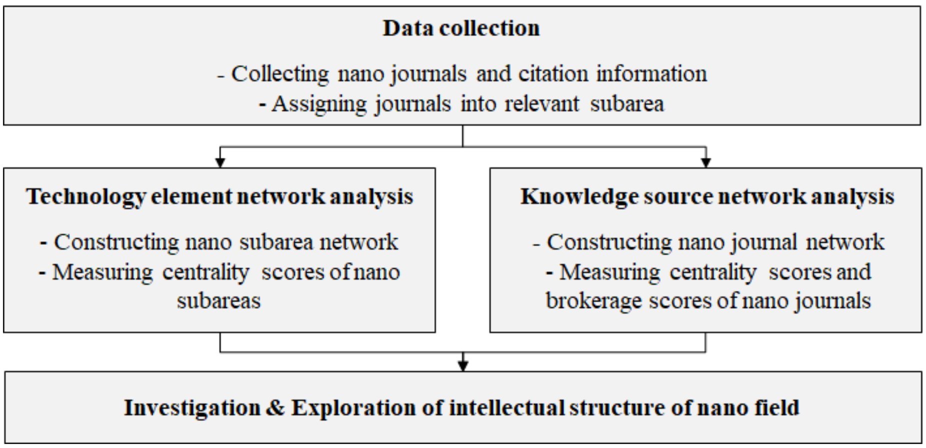

Figure 3-1 Overall process for identification of intellectual structure

3.3.2 Knowledge Source Selection

To examine the trends in nanoscience and nanotechnology (nano) field through a journal citation network analysis, a set of nano journals should be constructed first. However, defining relevant journals is difficult because nano is an emerging field and multidisciplinary in nature. There have been various attempts to deal with a fundamental question: which journals are in the field of nano? The attempts for searching nano journals can be divided into two ways. The first way is to search nano journals by setting core journals first and then extend a set of journals through investigating the citation relationships with core journals. Zhou and Leydesdorff (2006) used three core nano journals that include "nano" in their title, based on Science Citation Index (SCI) 2003. Furthermore, they enlarged the set of nano journals by considering "nano-relevant" journals. They defined a journal as nano-relevant if a journal has the citation relationships with any of the core journals and the extent of the citation is more than one percent of its total citation. As a result, 85 nano-relevant journals were collected. Similarly, Leydesdorff and Zhou (2007) could retrieve six core journals with "nano" in their title from SCI 2004. They found 67 nano-relevant journals instead of 85 journals. Moreover, they distinguished ten core journals using betweenness centrality that had been proposed by Leydesdorff (2007a) as a measure of interdisciplinarity.

The second way is to search nano journals by using Web of Science (WoS) Subject Category. In 2005, the new WoS Subject Category for nano, entitled "Nanoscience & Nanotechnology", entered the SCI with 27 journals. In recent study, Leydesdorff (2013) used 58 journals in the WoS Subject Category of "Nanoscience & Nanotechnology" to apply a new impact indicator to rank journals. Gorjiara and Baldock (2014) used a combined set of nano journals with lexical query method to retrieve nano publications from WoS and compare global and Australian nano publications. The combined set of nano journals included 42 journals that were suggested by Arora et al. (2013) and 66 journals that were harvested from the most current WoS Journal Citation Reports (JCR). Using WoS Subject Category is a straightforward method for searching nano journals. Also, the journals that are categorized as Subject Category of nano are updated annually and increased in their number because WoS JCR is published annually. Indeed, the number of journals that belong to nano Subject Category has been increased from 27 in 2005 to 73 by 2013. Therefore, WoS Subject Category was used to construct a set of nano journals. In the JCR 2013, the most current edition as of the time of this study (June 2014), 73 journals were categorized as nano journals. The list of the 73 nano journals and the abbreviation for them are given in Appendix C.

3.3.3 Technology Element Composition

Many studies have used SCI's Subject Categories to operationalize the concept of interdiscplinarity (Morillo et al. 2003; Van Raan 1999; Glanzel et al. 1999; Katz and Hicks 1995; Leydesdorff and Cozzens 1993; Moya-Anegon et al. 2004; Porter and Youtie 2009). Although Subject Category is useful and appropriate, it is not a perfect categorization (Porter and Youtie 2009). Many journals are categorized into two or more Subject Category. Moreover, Leydesdorff et al. (1994) and Hicks and Katz (1996) insisted that using Subject Category makes comparisons of trend difficult because it evolves.

In other studies, a set of technology elements of nano field was defined based on the expertise (OECD 2009; OECD 2010; OECD 2014;

Scheu et al. 2006). Although most of these studies were focused on a classification of the nano patents, the classification schemes specialized in nano field itself instead of mixed fields. Moreover, they are simple and practical. For example, Electronics, Instruments, Chemicals, Pharmaceuticals and biotechnologies, Industrial processing, Machinery, and Consumer goods and equipment were suggested as main fields of nano by OECD (2009). Besides that, European Patent Office (EPO) made new “Y01N” system to tag nano-related patent applications (Scheu et al. 2006; Hullmann 2006). Y01N system consists of six sub-codes: Y01N2 for Nanobiotechnology, Y01N4 for Nanoelectronics, Y01N6 for Nanomaterials, Y01N8 for Instruments, Y01N10 for Nanooptics, and Y01N12 for Nanomagnetics. Based on the Y01N system, B82Y, a new symbol, was introduced into International Patent Classification (IPC) system in 2011. Thus, Y01N codes are not used anymore. However, the core classification scheme of Y01N system is identical to that of B82Y system that is now included in both the IPC and the Cooperative Patent Classification (CPC) scheme.

Therefore, to compose the technology elements (i.e. sub-areas) of nano field, this study used the classification that was first suggested by European Patent Office (EPO). We added a technology element of “General” to the existing six elements to classify the journals that encompass a wide range of technology elements of nano. Then, we assigned each nano journal to the most appropriate technology element by considering various information of the journal such as journal’s Subject Category, aims, and scope. The classification scheme of nano field and a list of journals that belong to each technology element of nano are summarized in Table 3-1.

Table 3-1 Classification scheme of nano field and list of journals

Technology element	**Knowledge sources (journals)**
Biotechnology	BIOMED MICRODEVICES BIOMICROFLUIDICS DIG J NANOMATER BIOS IEEE T NANOBIOSCI IET NANOBIOTECHNOL INT J NANOMED J BIOMED NANOTECHNOL J NANOBIOTECHNOL NANOMED-NANOTECHNOL NANOMEDICINE-UK NANOTOXICOLOGY WIRES NANOMED NANOBI
Electronics	ACM J EMERG TECH COM BIOSENS BIOELECTRON J MICROMECH MICROENG J VAC SCI TECHNOL B MICROELECTRON ENG MICROELECTRON J MICROELECTRON RELIAB MICROSYST TECHNOL PLASMONICS
Instruments	J PHYS CHEM C MAT SCI ENG A-STRUCT MICROFLUID NANOFLUID MICROMACHINES-BASEL MICROPOR MESOPOR MAT NANO ENERGY NANOSC MICROSC THERM PHYSICA E PRECIS ENG
Optics	J LASER MICRO NANOEN J MICRO-NANOLITH MEM J NANOELECTRON OPTOE J NANOPHOTONICS PHOTONIC NANOSTRUCT

Magnetics	-
Materials	ACS APPL MATER INTER ADV FUNCT MATER ADV MATER J NANOMATER J NANOPART RES MATER EXPRESS MICRO NANO LETT REV ADV MATER SCI SCI ADV MATER SCRIPTA MATER SYNTH REACT INORG M
General	ACS NANO AIP ADV BEILSTEIN J NANOTECH CURR NANOSCI FULLER NANOTUB CAR N IEEE T NANOTECHNOL INT J NANOTECHNOL J COMPUT THEOR NANOS J EXP NANOSCI J NANO RES-SW J NANOSCI NANOTECHNO J PHYS CHEM LETT LAB CHIP NANO NANO LETT NANO RES NANO TODAY NANO-MICRO LETT NANOMATER NANOTECHNO NANOSCALE NANOSCALE RES LETT NANOSCI NANOTECH LET NANOTECHNOLOGY NAT NANOTECHNOL PART PART SYST CHAR RECENT PAT NANOTECH SMALL

3.4 Identification of Intellectual Structure

3.4.1 Macro View of Intellectual Structure

1) Network Construction

Based on the nanoscience and nanotechnology (nano) journal network, a technology element network was constructed. The binary 41 × 41 citation matrix was transformed into a valued 7 × 7 matrix by combining the journals that belong to the same technology element. Table 3-2 shows the 7 × 7 citation matrix for the nano technology element network. In Table 3-2, a citing technology element is a row, while a cited technology element is a column. The rows and the columns for technology elements of Optics (O) and Magnetics (Mg) are filled with zero because all journals in these technology elements have been eliminated during the matrix transformation.

Table 3-2 Valued matrix for technology element network

Technology element	**B**	**E**	**I**	**O**	**Mg**	**Mt**	**G**
B	0	0	0	0	0	0	6
E	0	3	2	0	0	3	10
I	0	0	4	0	0	6	12
O	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0
Mt	0	1	7	0	0	9	30
G	3	4	12	0	0	23	55

To visualize a citation network at technology element level, a direction of arrows was additionally defined. The citation relationship was represented as an arrow going from A to B if the journal A cites the journal B. This representation is concordance with the direction of citation. On the other hand, the reverse direction indicates the influence or knowledge flow. That's because if A cites B, B exerts an influence on A and the knowledge flows from B to A. Therefore, the reverse direction of the arrows was also considered for interpretation of the results. In brokerage analysis, the brokerage type was named in terms of knowledge flow, the reverse direction of citations.

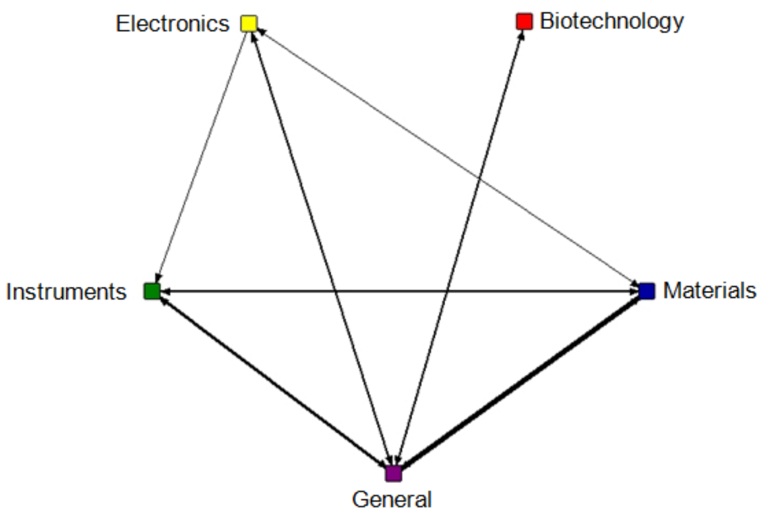

Figure 3-2 Nano technology element network

Figure 3-2 depicts the nano technology element network. However, five, instead of seven, technology elements are in the network because the technology element of Magnetics (Mg) and Optics (O) were disappeared in the network during the matrix transformation. The interactions between G and Mt, G and I, G and E, G and B, and I and Mt actively occurs, showing the thick links. In particular, G closely interacts with every technology elements and most strongly interacts with Mt, followed by I. Therefore, a knowledge exchange between G and Mt is expected to be the most active.

Excluding G, Mt and I are highly interlinked, and this represents that there is an active knowledge exchange between Mt and I. Specifically, the value that Mt cited I is 7, and the value that I cited Mt is 6. These results suggest a high importance of material interaction with instruments/equipments, and vice versa. In order to pattern a feature size less than 10nm, for instance, the extremely ultra-violet (EUV) photolithography equipment has been developed extensively as well as a suitable photoresist. Another example is the development of adhesive and temporary bonding de-bonding (TBDB) equipment in 3D stacking integration. Also, Mt is interlinked with E as well. As can be seen from Table 3-2, the value that Mt cited E is 1, while the value that E cited Mt is 3 in the technology element networks. To elaborate this technology element relationship, for example, the integrated circuit devices have been suffered from the limitation of physical scaling-down in a feature size. So it has been going through a major technology paradigm shift, which is focused on material and design. The related research fields are gate oxide material, FinFET (fin field effect transistor) structure, ultra-porous low k dielectrics, ultra-thin barrier material for Cu interconnection, photoresist for <10nm photolithography, and bonding material in 3D stacking integration.

When it comes to E, it also interacts with every technology element except for B. Especially, E has a one-way citation from E to I. Thus, E uses the knowledge from I, while I uses the knowledge mostly from G. To develop wafer-to-wafer bonder in 3D stacking integration, many equipment parts and parameters have to be developed, for example post bond alignment of 1-3 μm, stable and uniform bonding pressure, stacked wafer holder, clamp and spacer or manufacturing throughput. It needs certainly broad information from G, but it may not necessarily need from E. Furthermore, B is connected with only G, and it highly cites G rather than being cited by others. This suggests that B uses the knowledge mostly from G, but B's knowledge is rarely used by other technology elements. B is a unique technology element in terms of technology classification, because bio-technology has a tendency to get information from other technology elements and apply them to their own products. To fabricate a biochip that performs a biochemical reaction, conventional semiconductor processes or micro-electro-mechanical system (MEMS) methods are utilized frequently. In particular, if a research in B is related to biological and genetic science, then generally it is far away from other technology elements. This indicates that B is a strong absorber than any other technology elements. The technology element network analysis can be used to explore a macroscopic technology trend, and it helps both individual researchers and government to set their strategic research planning.

2) Centrality

The centrality scores of the technology elements are calculated based on the nano technology element network (Table 3-3). The number indicated in parentheses in Table 3-3 represents a rank regarding each centrality measure. As a whole, G and Mt are ranked the first and the second, respectively, across the five measures. Regarding out-degree and in-degree, I is ranked the third, E is ranked the fourth, and B is ranked the fifth regardless of the type of degree measure. When it comes to closeness, E is ranked the second along with Mt in terms of out-closeness while I is ranked the second along with Mt in terms of in-closeness. However, for betweenness, only G and Mt have a centrality score that exceeds zero. G is definitely central in the network in terms of betweenness. When we calculate the ratio of the in-degree to out-degree, G and I have a higher in-degree than out-degree. Hence they can be regarded as a knowledge supplier in the technology element network. On the other hand, Mt can be rather a knowledge absorber because it has a higher out-degree than in-degree. In addition, it is seen that E has the lowest ratio of the in-degree to out-degree, indicating that E is a strong knowledge absorber, relatively speaking, while G or Mt can be a knowledge absorber as well as supplier. This is understandable because the technology element E is the research fields strongly related to architecture, manufacturing, practical product, or device system in addition to some fundamental technologies. However, Mt is a knowledge absorber because material research is mostly based in a certain application, while Mt provides fundamental mechanism and process to other technology elements as a knowledge supplier. For example, p-type oxide semiconductor research is based in transparent electronic or optoelectronic applications, providing the control mechanisms of oxide defects and p-type conductivity. As a whole, G and Mt can be viewed as a knowledge distributor because they have a high level of every centrality measure even including betweenness. The technology element network analysis sufficiently explains the current technology trends and their macroscopic relationships setting up a future research scheme.

Table 3-3 Centrality of technology elements

Technology element	Out-degree	In-degree	Ratio (in/out)-degree	Out-closeness	In-closeness	Ratio (in/out)-closeness	Betweenness
B	1.000 (5)	0.500 (5)	0.500 (4)	0.462 (5)	0.462 (5)	1.000 (2)	0.000 (3)
E	2.500 (4)	0.833 (4)	0.333 (5)	0.545 (2)	0.500 (4)	0.917 (7)	0.000 (3)
I	3.000 (3)	3.500 (3)	1.167 (2)	0.500 (4)	0.545 (2)	1.091 (1)	0.000 (3)
O	0.000 (6)	0.000 (6)	-	0.333 (6)	0.333 (6)	1.000 (2)	0.000 (3)
Mg	0.000 (6)	0.000 (6)	-	0.333 (6)	0.333 (6)	1.000 (2)	0.000 (3)
Mt	6.333 (2)	5.333 (2)	0.842 (3)	0.545 (2)	0.545 (2)	1.000 (2)	1.667 (2)
G	7.000 (1)	9.667 (1)	1.381 (1)	0.600 (1)	0.600 (1)	1.000 (2)	21.667 (1)

3.4.2 Micro View of Intellectual Structure

1) Network Construction

For each of the 73 Nanoscience and nanotechnology (nano) journals, citation relationships among the journals were collected from the JCR 2013. The scope of the analysis is limited to direct relationships between the set of nano journals. Thus, the initial citation matrix was a valued 73 × 73 matrix. This citation matrix was then transformed into a binary matrix by setting cut-off value, which is a well-known method in social network analysis. To avoid a significant loss of information, the appropriate cut-off value was determined by adjusting the value slightly. As a result, cut-off value is set to be 130 because there was no significant change in big picture of the network until the cut-off value reaches 130 although the number of nodes was significantly reduced from 73 to 41. Therefore, the final citation matrix was obtained as a binary 41 × 41 matrix.

In visualizing a citation network at knowledge source level, the same definition of arrows' directions and the software, UCINET 6 and NetDraw were used. The nano knowledge source network that includes 41 journals as nodes is shown in Figure 3-3. UCINET 6 and NetDraw were used to build network matrix and to visualize the network, respectively. As described in section 3.3.3, each journal was assigned into relevant technology element. Based on that, journals were located in the network as a group of technology element, as shown in Figure 3-3. As shown in the nano technology element network, there are five, instead of seven, technology elements are in the network, including: Biotechnology (B), Electronics (E), Instruments (I), Materials (Mt), and General (G). Among the five technology elements,

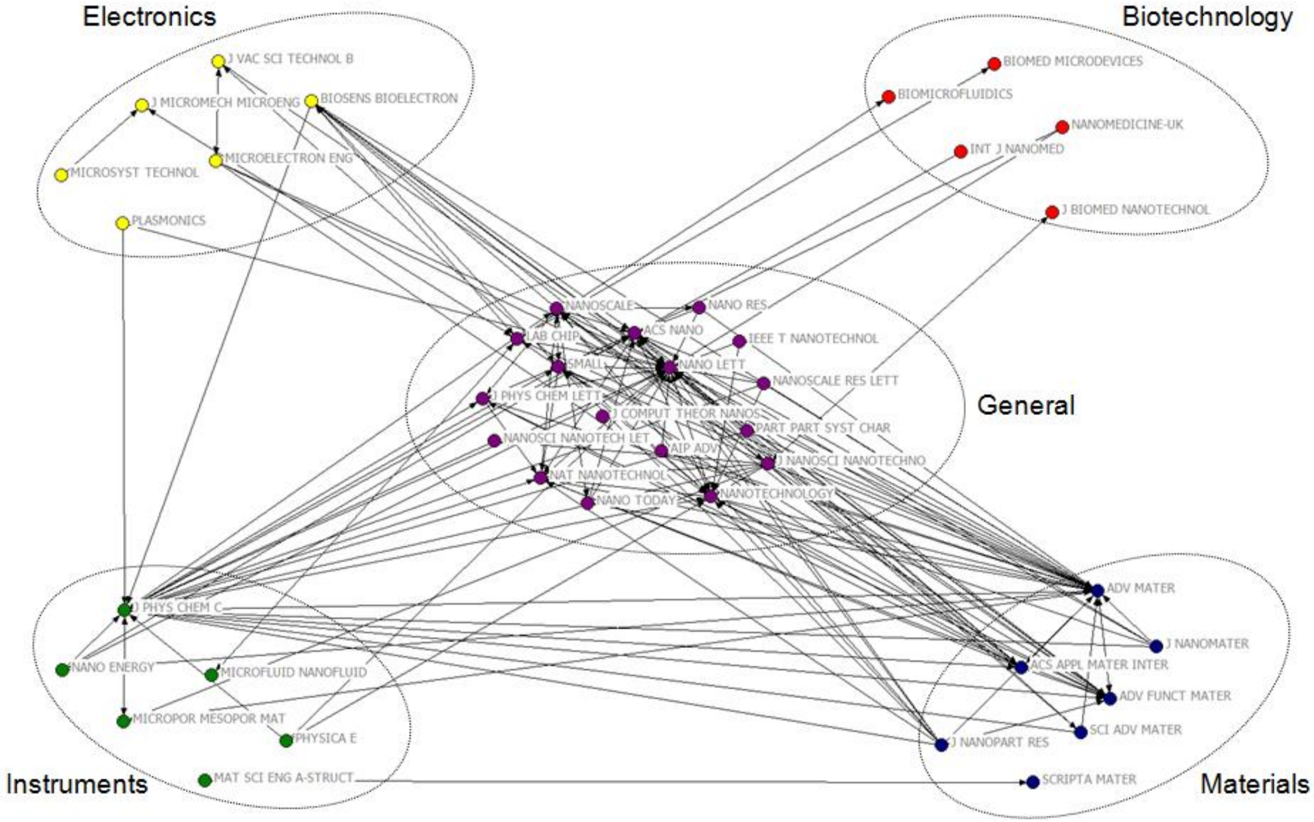

Figure 3-3 Nano knowledge source network

“General (G)” includes the majority of the journals, which are seventeen in total. Materials (Mt) is the second largest technology element that contains seven journals. Electronics (E), and Instruments (I) includes six journals, respectively. Biotechnology (B) contains five journals.

2) Centrality

To identify the core knowledge sources in the network, three indices, degree, closeness, and betweenness centrality, were measured. Table 3-4 summarizes the top 9 or 10 journals (knowledge sources) that earn the high centrality scores. The journals are in the order of their rank with the number that represents their centrality score. As a whole, the majority of the ranked journals are from G and Mt technology elements across all centrality measures. The one journal, J PHYS CHEM C, is from I and the one journal, J VAC SCI TECHNOL B, is from E. The centrality scores of the whole journals are given in Appendix D.

In terms of out-degree, NANOSCALE and J NANOSCI NANOTECHNO are ranked the first and the second, respectively. ACS APPL MATER INTER, ADV MATER, and J PHYS CHEM C are ranked third. Except for two journals, ACS APPL MATER INTER and J NANOPART RES, all journals in the list of the top 10 in terms of out-degree also have a high centrality score in terms of betweenness. When it comes to betweenness, ADV MATER is ranked the highest, followed by LAB CHIP and NANOSCALE. NANO LETT is ranked highest, followed by ADV MATER and J PHYS CHEM C in terms of in-degree. The top 9/10 journals (knowledge sources) and their rankings in terms of in-degree and in-closeness are the same except for two journals that ranked ninth and tenth. In comparison with the top 10 list of in-degree, J PHYS CHEM LETT, instead of NANOSCALE, is ranked ninth and NANOSCALE, instead of LAB CHIP, is ranked tenth regarding in-closeness. In addition, there is no change in the list of the top 9 journals (knowledge sources) in terms of out-degree and out-closeness, although the rankings are slightly changed.

When we compare the journals that are highly ranked in terms of out-degree and in-degree, J NANOSCI NANOTECHNO, ACS APPL MATER INTER, and J NANOPART RES have a high level of out-degree than in-degree. Thus, they actively cite other journals rather than being cited. In contrast, NANO LETT and NAT NANOTECHNOL have a high level of in-degree than out-degree. Hence, they are mainly cited by other journals and therefore, they can be considered a knowledge supplier in the network. ADV MATER, NANOSCALE, J PHYS CHEM C, NANOTECHNOLOGY, and ACS NANO have a high level of both out-degree and in-degree, and also they are ranked high for the betweenness centrality. Therefore, they can be viewed as a knowledge distributor in the network. Besides that, LAB CHIP, which has low level of out-degree and in-degree, is also considered as a knowledge distributor because it is the second highest-ranked in terms of betweenness. Similarly, J VAC SCI TECHNOL B is included in the top 10 list regarding betweenness centrality, although they have low level of out-degree and in-degree.

In addition, the impact factor (IF) of a journal that shows high centrality scores was investigated to find out whether the IF and centrality are related. Table 3-5 summarizes the IF value of top 9 or 10 journals (knowledge sources) that earn the high centrality scores. The rank of IF value among the 73 nano journals is presented in parentheses.

Table 3-4 Top 9/10 knowledge sources in terms of centrality

	Out-degree		In-degree		Out-closeness		In-closeness		Betweenness	
Rank	**Knowledge source**	**Score**	**Knowledge source**	**Score**	**Knowledge source**	**Score**	**Knowledge source**	**Score**	**Knowledge source**	**Score**
1	NANOSCALE	0.350	NANO LETT	0.725	NANOSCALE	0.274	NANO LETT	0.645	ADV MATER	16.840
2	J NANOSCI NANOTECHNO	0.300	ADV MATER	0.575	ADV MATER	0.270	ADV MATER	0.588	LAB CHIP	16.416
3	ACS APPL MATER INTER	0.275	J PHYS CHEM C	0.525	J NANOPART RES	0.268	J PHYS CHEM C	0.533	NANOSCALE	14.990
4	ADV MATER	0.275	ACS NANO	0.500	SMALL	0.267	ACS NANO	0.526	J NANOSCI NANOTECHNO	8.558
5	J PHYS CHEM C	0.275	NANOTECHNOL OGY	0.400	J NANOSCI NANOTECHNO	0.265	NANOTECHNOL OGY	0.500	J PHYS CHEM C	8.534
6	ACS NANO	0.250	ADV FUNCT MATER	0.300	J PHYS CHEM C	0.263	ADV FUNCT MATER	0.476	NANO LETT	8.391
7	J NANOPART RES	0.225	NAT NANOTECHNOL	0.300	ACS APPL MATER INTER	0.263	NAT NANOTECHNOL	0.476	NANOTECHNOLO GY	8.056
8	NANOTECHNOL OGY	0.225	SMALL	0.275	ACS NANO	0.261	SMALL	0.471	ACS NANO	5.799
9	SMALL	0.225	NANOSCALE	0.175	NANOTECHNOL OGY	0.261	J PHYS CHEM LETT	0.440	SMALL	3.574
10	NANO LETT	0.200	LAB CHIP	0.175			NANOSCALE	0.435	J VAC SCI TECHNOL B	2.372

In sum, when it comes to knowledge flows, a journal with high IF is not necessarily the central journal. In terms of out-degree, J NANOSCI NANOTECHNO is ranked high, but low in terms of IF. From the perspective of betweenness, two journals, J NANOSCI NANOTECHNO and J VAC SCI TECHNOL B are ranked in the top 10 despite their low IF.

The IF is defined as the number of citations, received in the current JCR year to items published in the previous two years, divided by the total number of articles published in the journal in the previous two years. Hence, the higher the IF, the higher the probability that the in-degree score will be high. In fact, the journals with high in-degree score also have high IF value as shown in Table 3-5. However, high score of out-degree does not mean high IF value because high out-degree indicates that a journal cites many others journals. J NANOSCI NANOTECHNO cites a lot of other journals although it is not cited much. Therefore, out-degree of this journal is high while its IF is low. In addition, as it cites many journals, it serves as a bridge in the path between two journals, and thereby has high betweenness centrality. On the other hand, J VAC SCI TECHNOL B has low score both of in-degree and out-degree while has high betweenness centrality. Even though J VAC SCI TECHNOL B neither cites much nor receives a lot of citations, it serves an important role in terms of knowledge flow. The reason is that it is the only journal that cites MICROELECTRON ENG. That means that every knowledge source should go through this journal for the path to MICROELECTRON ENG. In other words, the knowledge of MICROELECTRON ENG is propagated only through this journal in the current knowledge source network. Therefore, J VAC SCI TECHNOL B has high betweenness centrality although it has low IF.

Table 3-5 IF of top 9/10 knowledge sources in terms of centrality

	Out-degree		In-degree		Out-closeness		In-closeness		Betweenness	
Rank	**Knowledge source**	**IF (rank)**	**Knowledge source**	**IF (rank)**	**Knowledge source**	**IF (rank)**	**Knowledge source**	**IF (rank)**	**Knowledge source**	**IF (rank)**
1	NANOSCALE	6.739 (12)	NANO LETT	12.940 (4)	NANOSCALE	6.739 (12)	NANO LETT	12.940 (4)	ADV MATER	15.409 (3)
2	J NANOSCI NANOTECHNO	1.339 (51)	ADV MATER	15.409 (3)	ADV MATER	15.409 (3)	ADV MATER	15.409 (3)	LAB CHIP	5.748 (18)
3	ACS APPL MATER INTER	5.900 (16)	J PHYS CHEM C	4.835 (19)	J NANOPART RES	2.278 (34)	J PHYS CHEM C	4.835 (19)	NANOSCALE	6.739 (12)
4	ADV MATER	15.409 (3)	ACS NANO	12.033 (5)	SMALL	7.514 (9)	ACS NANO	12.033 (5)	J NANOSCI NANOTECHNO	1.339 (51)
5	J PHYS CHEM C	4.835 (19)	NANOTECHNOL OGY	3.672 (24)	J NANOSCI NANOTECHNO	1.339 (51)	NANOTECHNOL OGY	3.672 (24)	J PHYS CHEM C	4.835 (19)
6	ACS NANO	12.033 (5)	ADV FUNCT MATER	10.439 (6)	J PHYS CHEM C	4.835 (19)	ADV FUNCT MATER	10.439 (6)	NANO LETT	12.940 (4)
7	J NANOPART RES	2.278 (34)	NAT NANOTECHNOL	33.265 (1)	ACS APPL MATER INTER	5.900 (16)	NAT NANOTECHNOL	33.265 (1)	NANOTECHNOL OGY	3.672 (24)
8	NANOTECHNOL OGY	3.672 (24)	SMALL	7.514 (9)	ACS NANO	12.033 (5)	SMALL	7.514 (9)	ACS NANO	12.033 (5)
9	SMALL	7.514 (9)	NANOSCALE	6.739 (12)	NANOTECHNOL OGY	3.672 (24)	J PHYS CHEM LETT	6.687 (13)	SMALL	7.514 (9)
10	NANO LETT	12.940 (4)	LAB CHIP	5.748 (18)			NANOSCALE	6.739 (12)	J VAC SCI TECHNOL B	1.358 (49)

3) Brokerage Roles

Brokerage analysis was conducted to identify the roles in exchanging knowledge. Regarding the five brokerage types, the partial scores of each journal (knowledge source) in weighted version were obtained (Appendix E). Thirteen journals had a brokerage score of one and more for at least one brokerage type. Among them, eight journals' brokerage scores in total were extremely high compared to the other five journals. Most of the journals, six, that have a high brokerage score were from G. The other two journals were from I and Mt; one for each of the technology element. However, all three journals of E had low brokerage scores, which is one. None of the journals from B played a significant role as a knowledge broker. Table 3-6 describes the thirteen journals' brokerage role and their technology element with the brokerage scores in parentheses. Unlike other technology elements, there is no journal that plays a role of coordinator in E. In I, only one journal, J PHYS CHEM C, plays a role of every brokerage type; especially, the journal frequently acts as a representative and a liaison. When it comes to in Mt, ADV MATER performs a significant role as a broker for every brokerage types. This journal mainly functions as a consultant. In G, several journals play a role of each brokerage type. Among them, particularly, NANO LETT actively acts as a coordinator and LAP CHIP outperforms the other journals in terms of a liaison.

Table 3-6 Brokerage role of knowledge sources

Brokerage role	Technology element						
	B	**E**	**I**	**O**	**Mg**	**Mt**	**G**
Coordinator	-	-	J PHYS CHEM C (2)	-	-	ADV MATER (2)	ACS NANO (8), J NANOSCI NANOTECHNO (1), NANO LETT (22), NANOSCALE (9), NANOTECHNOLOGY (4), SMALL (3)
Representative	-	J VAC SCI TECHNOL B (1)	J PHYS CHEM C (17)	-	-	ADV MATER (10)	ACS NANO (13), J NANOSCI NANOTECHNO (6), LAB CHIP (4), NANO LETT (14), NANOSCALE (12), NANOTECHNOLOGY (6), SMALL (3)
Gatekeeper	-	J MICROMECH MICROENG (1)	J PHYS CHEM C (10)	-	-	ADV MATER (7)	ACS NANO (5), J NANOSCI NANOTECHNO (3), LAB CHIP (5), NANO LETT (11), NANOSCALE (5), NANOTECHNOLOGY (9)
Consultant	-	BIOSENS BIOELECTRON (1)	J PHYS CHEM C (13)	-	-	ADV MATER (23)	ACS NANO (1), LAB CHIP (4)
Liaison	-	BIOSENS BIOELECTRON (1)	J PHYS CHEM C (16)	-	-	ACS APPL MATER INTER (1), ADV MATER (13)	ACS NANO (7), J NANOSCI NANOTECHNO (5), LAB CHIP (24), NANO LETT (5), NANOSCALE (2), NANOTECHNOLOGY (10)

To investigate the brokerage roles of the nano journals in detail, technology element to technology element brokerage maps (brokerage maps) of each journal were used. In a brokerage map, the cell filled with a journal represents that the journal is a broker that transfer the knowledge from the technology element indicated in the column to the technology element stated in the row. The score presented with a journal in the cell shows the degree of brokerage role. Moreover, each cell can be specified as one of the coordinator, gatekeeper, representative, consultant, and liaison according to the definition of the brokerage types. For example, if the journal belongs to G, the cell from G to G represents the coordinator. The diagonal cells are consultant. The cells in the column G and the row G are representatives and gatekeepers, respectively. The rest cells are liaisons. On the other hand, if the journal belongs to the other technology element, the cells in the technology element to technology element table correspond to the different brokerage roles.

Therefore, the information of the technology element a journal belongs to was preserved when the brokerage maps of each journal were integrated into an aggregate form. In developing each brokerage map, the cell with a raw score under two was considered as an insignificant brokerage relationship and hence, eliminated. However, not to lose all information about the broker journals of E, the cell with a raw score of one was taken into account only when the journal belongs to E. As a result, the brokerage map was developed as shown in Table 3-7. In the brokerage map, journals that transfer the knowledge from the technology element indicated in the column to the technology element stated in the row are represented with the abbreviation of a technology element, they belong to, and the number that stands for the degree of brokerage role.

Table 3-7 Brokerage map of knowledge sources

	B	E	I	O	Mg	Mt	G
B	LAB CHIP (G, 2)	LAB CHIP (G, 4)	ACS NANO (G, 2), J NANOSCI NANOTECHNO (G, 2), LAB CHIP (G, 2),	-	-	ACS NANO (G, 5), J NANOSCI NANOTECHNO (G, 3), LAB CHIP (G, 2),	ACS NANO (G, 9), J NANOSCI NANOTECHNO (G, 6), LAB CHIP (G, 2), NANO LETT (G, 2)
E	LAB CHIP (G, 4)	LAB CHIP (G, 2)	J PHYS CHEM C (I, 2), LAB CHIP (G, 2),	-	-	J PHYS CHEM C (I, 2), ADV MATER (Mt, 2), NANO LETT (G, 2),	J MICROMECH MICROENG (E, 1), J PHYS CHEM C (I, 4), ADV MATER (Mt, 4), NANO LETT (G, 7), NANOTECHNOLOGY (G, 4),
I	LAB CHIP (G, 2)	LAB CHIP (G, 2), NANOTECHNOLOGY (G, 2)	J PHYS CHEM C (I, 2)	-	-	J PHYS CHEM C (I, 3), ADV MATER (Mt, 2),	J PHYS CHEM C (I, 7), ADV MATER (Mt, 7), NANO LETT (G, 3), NANOSCALE (G, 3), NANOTECHNOLOGY (G, 2),
O	-	-	-	-	-	-	-
Mg	-	-	-	-	-	-	-
Mt	LAB CHIP (G, 2)	NANOTECHNOLOGY (G, 5)	J PHYS CHEM C (I, 6),	-	-	J PHYS CHEM C (I, 2), ADV MATER (Mt, 2),	J PHYS CHEM C (I, 4), ADV MATER (Mt, 7), ACS NANO (G, 2), NANO LETT (G, 3), NANOSCALE (G, 9), SMALL (G, 2)
G	LAB CHIP (G, 2)	J VAC SCI TECHNOL B (E, 1), LAB CHIP (G, 2), NANOSCALE (G, 2), NANOTECHNOLOGY (G, 7)	BIOSENS BIOELECTRON (E, 1), J PHYS CHEM C (I, 9), ADV MATER (Mt, 2), NANO LETT (G, 4),	-	-	J PHYS CHEM C (I, 6), ADV MATER (Mt, 7), ACS NANO (G, 4), NANO LETT (G, 7),	BIOSENS BIOELECTRON (E, 1), J PHYS CHEM C (I, 11), ADV MATER (Mt, 23), ACS NANO (G, 8), NANO LETT (G, 22), NANOSCALE (G, 9), NANOTECHNOLOGY (G, 4), SMALL (G, 3)

First, when it comes to technology element E's knowledge sources, three journals, J VAC SCI TECHNOL B, J MICROMECH MICROENG, and BIOSENS BIOELECTRON, were knowledge brokers although they were all weak. Specifically, J VAC SCI TECHNOL B transfers the E's knowledge to G as a representative. On the other hand, J MICROMECH MICROENG transfers the G's knowledge to E as a gatekeeper. In addition, BIOSENS BIOELECTRON delivers I's knowledge to G as a liaison. It also performs a role as a consultant for G.

Second, regarding the technology element I's knowledge sources, only J PHYS CHEM C was a knowledge broker. However, this journal played a role of all brokerage types. J PHYS CHEM C transfers the knowledge from Mt to E and G and from G to E and Mt as a liaison. This journal also distributes I's knowledge to E, Mt, and G as a representative and absorbs Mt's and G's knowledge into I as a gatekeeper. It plays a role as a coordinator for I and a consultant for G and Mt as well.

In terms of the technology element Mt's knowledge sources, two journals, ADV MATER and ACS APPL MATER INTER, were knowledge brokers. Among two, ADV MATER played a significant role in the brokerage map. ADV MATER transfers the knowledge from G to E and I and from I to G as a liaison. It also delivers the Mt's knowledge to E and I as a representative. Furthermore, this journal mediates Mt and G as a gatekeeper and a representative. It is a strong consultant for G while being a weak coordinator for Mt.

Lastly, regarding the technology element G's knowledge sources, the journals that play a brokerage role were seven, including: ACS NANO, J NANOSCI NANOTECHNO, LAB CHIP, NANO LETT, NANOSCALE, NANOTECHNOLOGY, and SMALL. LAB CHIP is unique in that it delivers the B’s knowledge to all the other technology elements and B itself. Also, it is the only broker that transfers the E’s knowledge to B as a liaison and to E itself as a consultant. The E’s knowledge is conveyed to I, Mt, and G by NANOTECHNOLOGY as well. Furthermore, ACS NANO delivers I’s and Mt’s knowledge to B as a liaison. It also plays a role as a gatekeeper along with NANO LETT transferring the knowledge from Mt to G. In addition, at least two journals of G distribute the knowledge from G to the other technology elements as a representative. The five journals, which are ACS NANO, NANO LETT, NANOSCALE, NANOTECHNOLOGY, and SMALL are coordinator for G. Among them, NANO LETT is the strongest coordinator.

3.5 Conclusion

In this study, to explore the interdisciplinary characteristics of nano field and investigate its intellectual structure, nano knowledge source network and nano technology element network were constructed and analyzed with centrality and brokerage measures. Specifically, the journals with high centrality scores were identified as important knowledge sources in the knowledge source network, which shows the overall structure of nano field, in terms of knowledge flow. Furthermore, the specific role of each knowledge source in exchanging knowledge was identified by brokerage analysis. In addition, from the view of technology element level, the position of each technology element was investigated regarding the knowledge flow in nano field.

As nano field has gained huge investments from governments as well as big interests from researchers, understanding the research trends of nano field is important to both governments and researchers. This study provides overall view of intellectual structure of nano field based on the empirical data and quantitative analysis. Especially, this study can contribute to the field of studying intellectual structure of nano by identifying specific role of each knowledge source in terms of intermediate relationships in knowledge flow. Thereby this study is expected to help researchers to find proper knowledge source for acquiring knowledge and new research opportunities.

However, there are some aspects that could be improved in future research. Firstly, future research could use other additional measures for structural characteristics of the nano knowledge source/technology element network. Although the centrality and brokerage measures have provided useful information in this study, the inclusion of other network measures such as density and average paths can allow richer understanding about the structure of nano field. Secondly, the brokerage analysis could be improved by considering different settings of affiliation. To operationalize the brokerage analysis, all journals were assigned to the only and a single technology element of nano field. However, in fact, journals can be categorized into two or more nano technology elements and thus, the result of brokerage analysis can vary depending on the affiliation settings of journals. Therefore, tracking the changes of brokerage results according to the affiliation settings of journals could provide new implications about the role of knowledge sources as a knowledge broker. Also, because only the data from the JCR 2013 was analyzed in this study, future research could include more data from different period. Comparing the structure of nano field at different period could suggest some evidence of evolutionary patterns of nano field's intellectual structure.

Chapter 4

Managing Convergence in Complexity

4.1 Introduction

Technological convergence, a blurring and redefinition of existing boundaries between two or more areas of technology, has been an important source of innovations in recent years (Curran and Leker, 2011; Karvonen and Kässi, 2013). This phenomenon creates new technological fields and leads to emerging technology and industry sectors (Song et al., 2017). Thus, emerging technologies are generated and developed based on technological convergence in many cases, resulting in more convergence. Therefore, understanding and forecasting the trends of technological convergence is important in monitoring emerging technologies and pursuing sustainable innovation and economic growth (Lee et al., 2015).

However, it is difficult to forecast technological convergence because the patterns of technological improvements are diverse and dynamic as markets and technologies change rapidly. Moreover, emerging technology is characterized by five main attributes: (1) radical novelty, (2) relatively fast growth, (3) coherence, (4) prominent impact, and (5) uncertainty and ambiguity (Rotolo et al., 2015). Due to such characteristics of emerging technologies, it is more difficult to predict technological convergence in emerging fields.

Patents have been considered as a regular source of information to gain insight into technological convergence because it is an ample source for technical and commercial knowledge (Ernst, 2003). Specifically, patent co-classification has been widely used as an indicator of technological connections and knowledge flows (Leydesdorff 2008; Karvonen and Kässi, 2011; Geum et al., 2012). In addition, recent studies have applied the concept of modern network science to patent data to analyze the overall structure of patents and technologies because patent co-classification can be interpreted as a network structure (Érdi et al., 2013; Cho et al., 2015). Such patent network analysis has gained attention for the advantages in that it can easily visualize the relationships between patents, quantitatively analyze the position of individual patents, and find focal patent in the network. Despite these advantages, previous attempts are not suitable for predicting technological convergence of new, rapidly changing and uncertain promising technologies because they were limited to an ex-post analysis by focusing only on the nodes of a network.

Link prediction method can be a remedy for this limitation because it is an attempt to estimate the likelihood of the existence of a link between two nodes in the future based on observed links and the attributes of nodes (Getoor and Diehl, 2005). Therefore, this paper aims to propose an ex-ante approach wherein patent co-classification analysis and link prediction are used to predict technological convergence in emerging fields. The proposed approach is illustrated with the case of 3D printing technology.

4.2 Convergence of Emerging Technologies

4.2.1 Understanding of Emerging Technology

Emerging technologies have been the subject of much attention in academic research as well as in policy discussion (Rotolo et al., 2015). Especially, monitoring emerging technologies is regarded as an invaluable step of research and development (R&D) policy by governments and companies (Ashton et al., 1991). Therefore, there has been a number of studies across diverse topics including characterizing and analyzing emerging technologies.

Emerging technologies have the following features: (1) radical novelty, (2) relatively fast growth, (3) coherence, (4) prominent impact, (5) uncertainty (Rotolo et al., 2015). The first feature, radical novelty means "novelty (or newness)" (small et al., 2014) that may appear as "discontinuous innovations" of either the method or the function of the technology (Day and Schoemaker, 2000). Emerging technologies build on different basic principles for a new function (Arthur, 2007). Secondly, emerging technologies have "clockspeed nature" (Srinivasan, 2008) or "fast growth" (Cozzens et al., 2010) that can be observed as an increase in various dimensions such as the number of actors involved, funding, papers, patents, etc. The third feature, coherence indicates ″convergence of previously separated research streams" (Day and Schoemaker, 2000) or technologies that "have already moved beyond the purely conceptual stage" (Stahl, 2011). The fourth feature, prominent impact points out that emerging technologies "create a new industry or transforms existing ones" (Day and Schoemaker, 2000) or "change the basis of competition" (Hung and Chu, 2006). Finally, emerging technologies are concerned with uncertainty and ambiguity in terms of the possible outcomes including potential applications of the technology (Stirling, 2007).

These features have different levels over time while emerging technologies pass through three stages which are pre-emergence, emergence, post-emergence (Rotolo et al., 2015). In the pre-emergence stage, the first stage of emergence, a technology has high levels of radical novelty and uncertainty, but low levels of prominent impact, coherence and growth rate. In the emergence stage, the technology becomes more coherent and shows fast growth such as a rapidly growing number of patents, papers, products, etc. During this stage, the features dramatically change over time. When the technology enters in the post-emergence stage, impact and growth become stable, but radical novelty and uncertain reach low levels.

In this regard, the convergence patterns of emerging technologies may vary according to each stage. This study suggests a new approach for predicting technological convergence of emerging technologies by considering the stages of emergence and using the ex-ante method. In order to consider the change of features of emerging technologies depending on their stages, diverse indices for link prediction method are applied to each stage.

4.2.2 Technological Convergence Analysis using Patents

Previous studies analyzing the technological convergence phenomenon mainly used patent information for the purpose of quantitative analysis. In recent years, a patent network analysis has received great attention from researchers because it can visualize the linkages between technology fields as a network form and identify the characteristics or core subjects of convergence by quantitatively examining the network characteristics (Érdi et al., 2013; Cho et al. 2015). As a method for constructing a patent network, co-citation, co-classification, and co-word analysis of patent information were used (Wagner et al., 2011).

In particular, co-classification analysis has been widely used in many studies because it has relatively low probability of error due to time difference since it is based on the patent classification information that was defined beforehand (Park and Yoon, 2014; Song et al., 2017). For instance, Curran and Leker (2011) conducted IPC (International Patent Classification) co-classification analysis for monitoring of converging industries. Geum et al. (2012) investigated the technological convergence between biotechnology (BT) and information technology (IT) using patent co-classification analysis along with patent citations. Lee et al., (2015) analyzed IPC co-classification using association rule and link prediction methods to predict the patterns of technological convergence. Song et al., (2017) presented a method based on IPC co-classification analysis to depict the relationships among technology classes and detect weak signals of technological convergence.

However, most of the prior studies that analyze technological convergence using patent networks relied on an ex-post analysis that considers only the observed data from a static point of view. Although there was an attempt to predict the technological convergence in advance by using link prediction (Lee t al., 2015), it is not suitable for predicting technological convergence of new, rapidly changing and uncertain promising technologies since it uses a single feature of networks for link prediction through every time period.

4.3 Research process

4.3.1 Overall Process

The research process for the proposed approach is composed of four steps (Figure 4-1). Firstly, patents related to the target technology and their classification information (i.e. IPCs) are collected over time from the USPTO database. Furthermore, the collection period is divided into several periods according to emergence stages. Secondly, patent co-classification networks for each period are constructed based on the collected data. Thirdly, through the link prediction process, the prediction accuracy of network features is validated, and the important features that provide good prediction results are identified for each period. Lastly, the characteristics of technological convergence in each stage are investigated, and the future patterns of technological convergence are predicted based on the information derived from the former step.

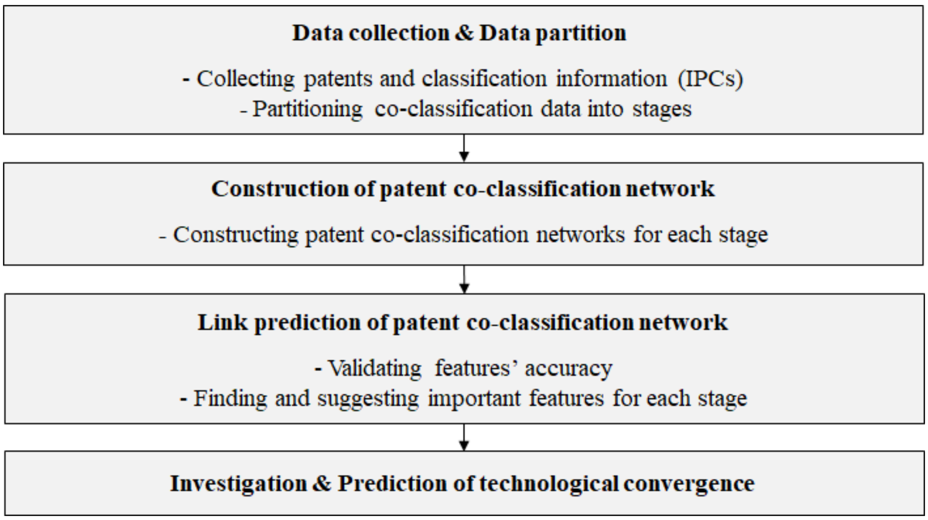

Figure 4-1 Overall process for prediction of technological convergence

4.3.2 Detailed Process

1) Data Collection and Data Partition

In the first step, the patents and their IPC information are collected over time from the USPTO database. The IPC code has a section, class, subclass, main group and subgroup (e.g. G03C 7/14). However, IPC subclass level (i.e. 4-digit IPC code; e.g. G03C) is used in this study because it is shown to be sufficient to represent characteristics of technological fields related to a patent (Guan and He, 2007; Chen et al., 2010; Wang et al., 2011). Consequently, the database of patents including their publication dates and 4-digit IPC codes are constructed.

Then the database is divided by several periods according to emergence stages of emerging technologies. As described in section 4.2.1, the emergence stage is divided into three stages in the previous research, and the degree of "growth" characteristic appears as S-curve over time as an emerging technology passes three stages. This characteristic is reflected in the number of patents, and thereby the period corresponding to each emergence stage can be identified by counting the patents over time. However, for some technologies that have not yet reached the third stage, the second stage, "emergence," is divided into two stages of "incremental-emergence" and "radical-emergence." In addition, the last stage is divided again into two stages (e.g. radical-emergence 1 and radical-emergence 2) to apply the link prediction method to the last stage afterward.

2) Patent Co-classification Network Construction

In the second step, the partitioned data is described by a co-classification network, where nodes represent IPC classes and edges represent co-classification relationships between them, for each period. Specifically, when a patent has multiple IPC codes, all combinations of them are considered as co-classification relationships. For example, if a patent is classified into multiple IPC codes, A, B, C, the links between A and B, B and C, and C and A are considered as undirected co-classification relationships. Therefore, this process identifies all links among IPCs that are assigned to the same patent. Then the links among IPCs become edges, and the IPCs that constitute the links become nodes in the network. Here, it is assumed that an IPC subclass represents a technology field, and a co-classification link represents an evidence of technological convergence as well as a linkage between technology fields.

3) Link Prediction of Patent Network

In the third step, the link prediction method is applied to patent co-classification network to find a good network feature for prediction of technological convergence, and examine the characteristics of convergence patterns according to each stage. First of all, the network features are defined and categorized based on the basic link prediction indices used by prior studies. Specifically, common neighbors (CN) and Jaccard indices are selected as the neighbor-based features; local path index (LP) is selected as the path-based feature; preferential attachment index (PA) is selected as the attribute-based feature. In addition, the product of two nodes' centrality score, such as degree, closeness, and betweenness, is considered as the attribute-based feature. Centrality is a measure that is widely used to find core nodes in networks and to quantify how important they are relative to others (Freeman, 1979). There are three indices for centrality according to how we view a node as central. (1) Degree: a node that is linked with many other nodes is more central. (2) Closeness: a node that can reach other nodes through short distance paths is more central. (3) Betweenness: a node that lies in the path between other nodes is more central. Although centrality is a measure for nodes, the product of centrality scores of two nodes can be a useful feature of a link. However, the product of degree centrality scores is not selected since it is identical with PA by its definition.

Table 4-1 summarizes six features used for link prediction in this study. Following the notation from Liben-Nowell and Kleinber (2007), Γ(i) denotes the set of neighbors of i in the network. CN indicates the number of neighbors that node i and j have in common. Jaccard refines the simple counting of CN by normalizing the size of CN. LP is a measure that considers local paths with length two and three. In description, $path_{i,j}^{<l>}$ is the path of length l from node i to j. To give more weight to the path of length two, an adjustment factor ϵ is applied in the measure. ϵ should be a small number close to zero. PA is defined as the product of the number of links of i and j. This feature is identical with the product of the degree centrality scores of two nodes. Closeness product (Closeness) and betweenness product (Betweenness) indicate the product of the closeness and betweenness centrality scores of two nodes respectively.

Table 4-1 Network features for link prediction

Feature set	**Feature**	**Description**
Neighbor-based	Common-neighbors (CN)	$\|\Gamma(i) \cap \Gamma(j)\|$
	Jaccard index (Jaccard)	$\frac{\|\Gamma(i) \cap \Gamma(j)\|}{\|\Gamma(i) \cup \Gamma(j)\|}$
Path-based	Local path index (LP)	$\left\|path_{i,j}^{<2>}\right\| + \epsilon \cdot \left\|path_{i,j}^{<3>}\right\|$
Attribute-based	Preferential attachment (PA)	$\|\Gamma(i)\| \cdot \|\Gamma(j)\|$
	Closeness product (Closeness)	Closeness (i) * Closeness (j)
	Betweenness product (Betweenness)	Betweenness (i) * Betweenness (j)

Then, to validate the accuracy of network features, the six features are evaluated by two standard metrics: area under the ROC curve (AUC) and Precision. AUC can be interpreted as the probability that a randomly chosen missing link (i.e. a link in the present network) has a higher score than a randomly chosen non-existent link. If AUC value exceeds 0.5, the algorithm's performance is better than pure chance and the gap between the AUC value and 0.5 indicates how better the algorithm predicts than pure chance. Precision is defined as the ratio of the number of true positive to the number of predicted positive (i.e. true positive/(true positive + false positive)). Therefore, higher AUC and higher precision mean higher algorithm's performance, prediction accuracy. Consequently, the feature that has high AUC or precision is identified as the important feature for each period.

4) Investigation and Prediction of Technological Convergence

In the final step, the characteristics of technological convergence are investigated for every stage base on the important feature derived from the previous step. Future, future patterns of technological convergence are predicted using the feature that show the highest performance in the last stage under the assumption that the technology will continue to be in the last stage of emergence in the future. The links that have higher scores than a threshold value are selected as promising links. Finally, potential technological fields of convergence are suggested by analyzing the nodes that constitute the promising links.

4.4 Prediction of Technological Convergence

4.4.1 Background

A case study of 3D printing technology was conducted to illustrate how the proposed approach can provide useful information of technological convergence. 3D (three-dimensional) printing technologies have gained increasing importance not only in various fields of business, but also in people's daily lives (Rayna and Striukova, 2016). The technology is associated with diverse technologies such as laser beams and materials and hence it is a converging technology where a three dimensional object is created by laying down successive layers of material (Mishra, 2014; Park et al., 2016). It is also known as additive manufacturing or rapid prototyping.

4.4.2 Data Collection and Data Partition

In order to collect the patents related to 3D printing technology, patents that have the word "3D printing/print/printer" or "additive manufacturing" or "rapid prototype" or their variants such as "rapid manufacturing" or "three-dimensional manufacturing" in their titles or abstracts were collected from USPTO database. We focused on the patents issued during 1976-2016. After eliminating unrelated patents, 2932 patents were collected. The 4-digit IPCs of each patent were also collected to generate co-classification links. As a whole, 3978 co-classification relationships among 336 IPCs were found after removing redundant relationships.

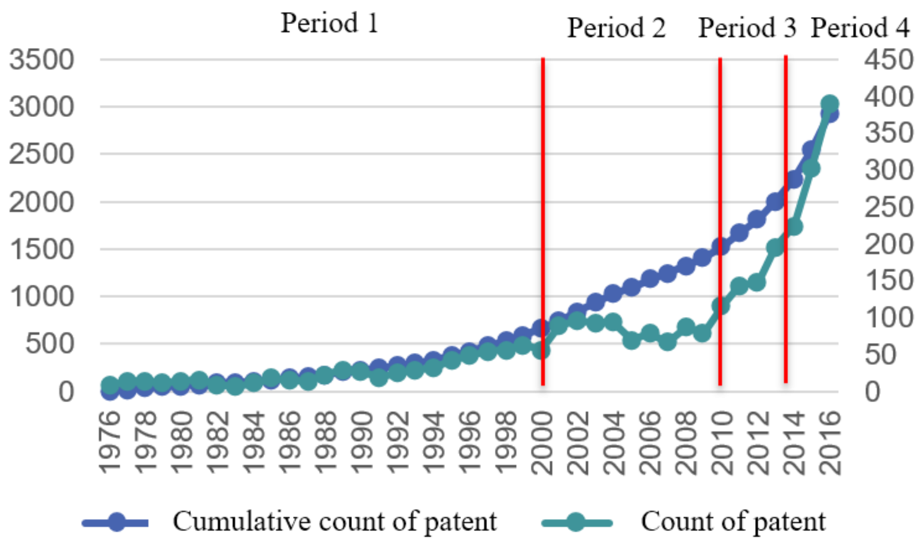

Figure 4-2 Cumulative count of patents related to 3D printing

Then the collection period was divided into four periods by investigating the count of patents and considering the emergence stages of emerging technologies (Figure 4-2). The period 1 to 4 correspond to pre-emergence (1976~2000), incremental-emergence (2001~2010), radical-emergence 1 (2011~2014), and radical-emergence 2 (2015~2016) stages. Specifically, based on the cumulative count of the patents, the year where the count of patents changes rapidly became a point of division. Because the 3D printing technology was appeared to be in the radical-emergence stage as the last stage, this stage is divided again into two stages (i.e. radical-emergence 1 and radical-emergence 2) to conduct link prediction method in a later step. Table 4-2 summarizes the description of data in each period. In Table 4-2, the number of links is the number of co-classification links in each period after removing redundant links.

Table 4-2 Summary of partitioned data

Stage	**Period**	**Number of patents**	**Number of links**
Pre-emergence	1 (1976~2000)	657	1642
Incremental-emergence	2 (2001~2010)	870	1286
Rapid-emergence 1	3 (2011~2014)	712	710
Rapid-emergence 2	4 (2015~2016)	693	1708
Total	1~4 (1976~2016)	2932	3978

4.4.3 Patent Co-classification Network Construction

The patent and their co-classification data of each period were depicted as a network, where a node is an IPC subclass (i.e. 4-digit IPC code) of 3D printing patents and a link is a co-classification relationship between IPC subclasses. All links in the networks were transformed into unweighted edges. Namely, all networks were transformed into binary networks. As shown in Table 4-2 and Figure 4-3, the network for period 1 included 657 patents and 1642 co-classification links; the network for period 2 included 870 patents and 1286 co-classification links; the network for period 3 included 712 patents and 710 co-classification links; the network for period 4 included 693 patents and 1708 co-classification links. Although the duration of the period was decreasing, the number of patents included in each period were similar or increased. Especially, the number of co-classification links has increased explosively in period 4 even though it was the shortest period.

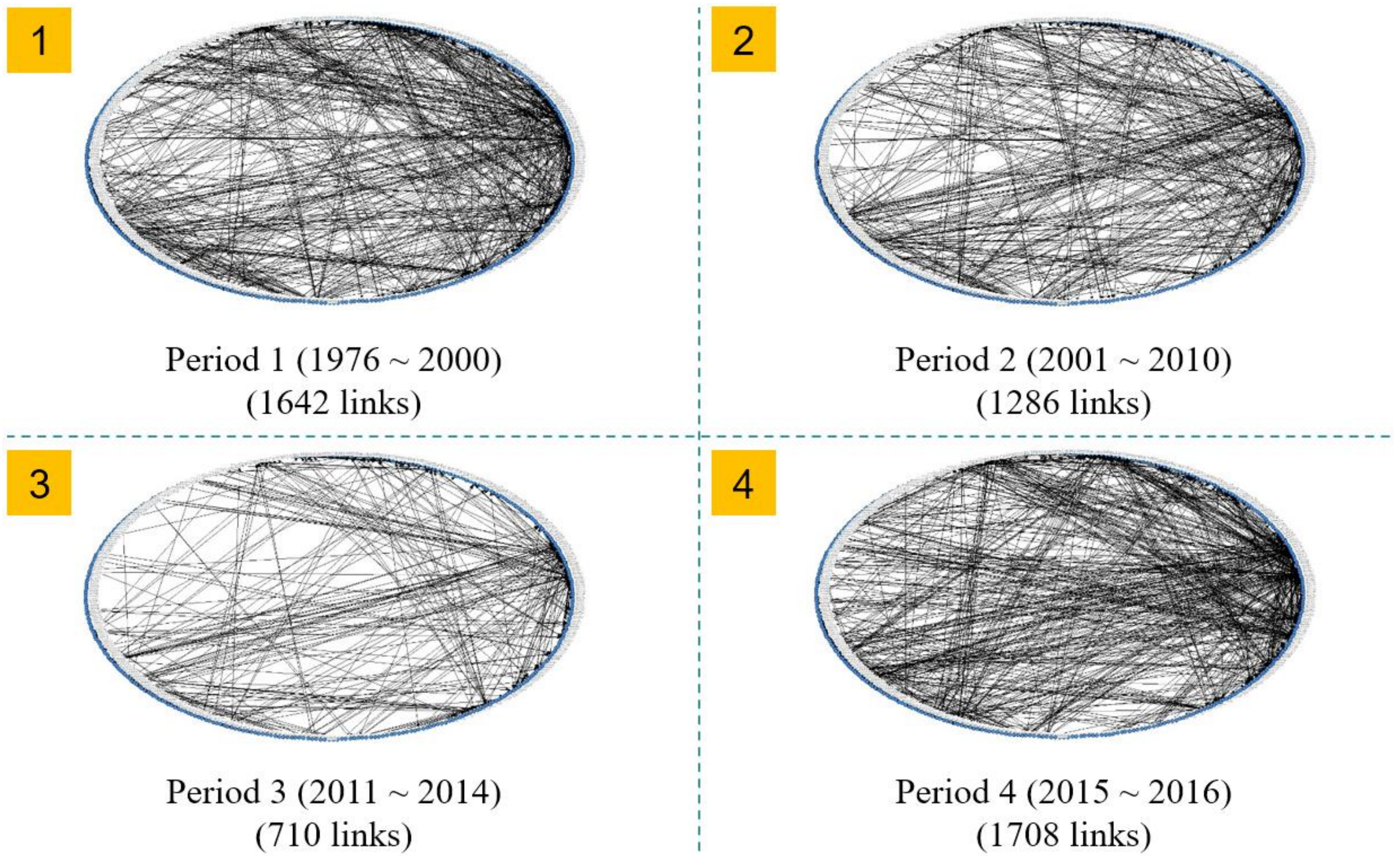

Figure 4-3 Patent co-classification network of each period

4.4.4 Link Prediction of Patent Network

The link prediction was applied to patent co-classification network to find a good network feature for prediction of technological convergence, and hence provide meaningful prediction of future convergence. The six indices of three categories were used for link prediction as follows: (1) Neighbor-based features: Common neighbors (CN) and Jaccard index (Jaccard); (2) Path-based feature: Local path index (LP); (3) Attribute-based features: Preferential attachment index (PA), Closeness product (Closeness), and Betweenness product (Betweenness) (Table 4-1). They have been used frequently in many studies and have shown a good prediction depending on distinct characteristics of a network. As each index reflects the characteristics of a network, the six indices were treated as network features, and the network features were calculated across all co-classification networks of four periods.

Then a supervised approach, in which the link prediction is treated as a binary classification problem, was used as a framework of link prediction. Specifically, a decision tree approach is used by treating the presence of links in the period n+1 network as a target variable and the network features calculated from the period n network as input variables. In addition, to prevent a class bias issue, oversampling of the minority class (i.e. positive target value that means the existence of a link) was conducted for learning process of the decision tree model.

Finally, the network features were evaluated by two standard metrics: Precision and AUC. Precision was calculated from the result with oversampling at first, and then adjusted to offset the effect of oversampling. AUC was also derived considering the whole data set after learning the decision tree model with oversampling.

Table 4-3 shows the performance of each feature when they were used to predict the links in period 2 network. Among the six features, CN and Jaccard were found to be the best predictors on the basis of AUC. AUC value of CN and Jaccard was 0.78. When it comes to precision, LP and PA were the best predictors. The adjusted value of precision of them was 0.1. However, AUC is considered as a more robust measure in the presence of class imbalance (Wang et al., 2015). Therefore, neighbor-based features, CN and Jaccard, were determined to be important features for predicting links in period 2.

Table 4-3 Result of prediction for period 2

Period 1→2	**CN**	**Jaccard**	**LP**	**PA**	**Closeness**	**Betweenness**
Precision	0.85	0.85	0.92	0.92	0.86	0.89
Adjusted Precision	0.05	0.05	0.10	0.10	0.06	0.07
AUC	0.78	0.78	0.77	0.76	0.76	0.74

The result of link prediction for period 3 is shown in Table 4-4. Unlike the former result, LP was found to be the most important feature for predicting links in terms of AUC.

Table 4-4 Result of prediction for period 3

Period 2→3	**CN**	**Jaccard**	**LP**	**PA**	**Closeness**	**Betweenness**
Precision	0.91	0.91	0.91	0.92	0.92	0.91
Adjusted Precision	0.05	0.05	0.05	0.06	0.06	0.05
AUC	0.74	0.74	0.75	0.74	0.72	0.71

When predicting the network of period 4 based on the information of period 3, Closeness showed the highest AUC value (Table 4-5). In sum, CN, Jaccard, LP, and Closeness features were found to be important features for predicting links across the periods. Moreover, the important feature was changed over periods as follows: Neighbor-based, Path-based, and Attribute-based in sequence.

Table 4-5 Result of prediction for period 4

Period 3→4	**CN**	**Jaccard**	**LP**	**PA**	**Closeness**	**Betweenness**
Precision	0.92	0.92	0.89	0.86	0.75	0.90
Adjusted Precision	0.13	0.13	0.09	0.07	0.04	0.11
AUC	0.64	0.64	0.66	0.67	0.73	0.61

4.4.5 Investigation and Prediction of Technological Convergence

To predict the future of the last period, Closeness was used because it showed good performance when predicting period 4 and it is assumed that the technology will continue to be in the last stage for quite a while. The existence likelihood of each link was calculated by Closeness feature and top ranked links were selected as future links. The threshold of existence likelihood of link was set considering the decision tree model used for the prediction of period 4, and the number of links predicted to exist.

As a result, the future network was obtained by calculating Closeness feature of the network in period 4 as shown in Figure 4-4. The future network contained 2303 links. There was a big change in composition of links compared to those in period 4. Among them, 798 links were the same links that existed in the period 4 network; 1505 links were new links that didn't exist in the period 4 network.

Specifically, among the newly rising links (i.e. links predicted to appear in the future but not connected in period 4), top ranked links were identified to gain insights of technological convergence that has high probability of emergence. After eliminating self-loops and duplicated links, top five pairs between eight IPCs were obtained as follows: (B33Y, H01L), (B33Y, B82Y), (B29C, C03C), (B33Y, C23C), (B32B, G03F). According to the description of IPCs, potential technology fields of convergence were identified as shown in Table 4-6. The convergence is expected to arise among the field of additive manufacturing, semiconductor devices, applications of nanostructures, shaping or joining of plastics, chemical composition of glasses, coating metallic material, layered products, and photomechanical production of textured or patterned surfaces.

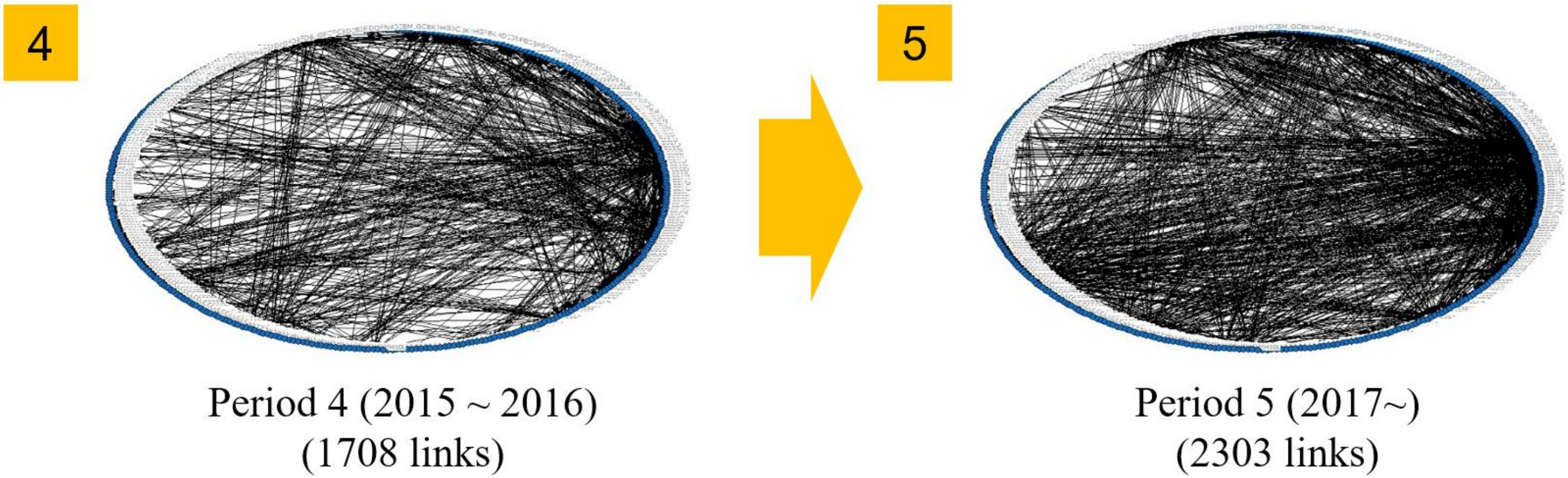

Figure 4-4 Prediction of future network

Table 4-6 Description of IPCs that constitute promising links

No.	IPC	Description
1	B33Y	Additive manufacturing, i.e. manufacturing of three-dimensional [3D] objects by additive deposition, additive agglomeration or additive layering, e.g. by 3D printing, stereolithography or selective laser sintering
2	H01L	Semiconductor devices; electric solid state devices not otherwise provided for
3	B82Y	Specific uses or applications of nanostructures; measurement or analysis of nanostructures; manufacture or treatment of nanostructures
4	B29C	Shaping or joining of plastics; shaping of material in a plastic state, not otherwise provided for; after-treatment of the shaped products, e.g. repairing
5	C03C	Chemical composition of glasses, glazes, or vitreous enamels; surface treatment of glass; surface treatment of fibres or filaments from glass, minerals or slags; joining glass to glass or other materials
6	C23C	Coating metallic material; coating material with metallic material; surface treatment of metallic material by diffusion into the surface, by chemical conversion or substitution; coating by vacuum evaporation, by sputtering, by ion implantation or by chemical vapour deposition, in general
7	B32B	Layered products, i.e. products built-up of strata of flat or non-flat, e.g. cellular or honeycomb, form
8	G03F	Photomechanical production of textured or patterned surfaces, e.g. for printing, for processing of semiconductor devices; materials therefor; originals therefor; apparatus specially adapted therefor

In addition, the most promising convergence between those technology fields is summarized in Table 4-7. It is expected that the field of additive manufacturing will be actively converged with the field of semiconductor devices, applications of nanostructures, and coating metallic material in the near future. Other convergence is expected to emerge between the field of shaping or joining of plastics and chemical composition of glasses, glazes, or vitreous enamels as well as between the field of layered products and photomechanical production of textured or patterned surfaces.

Table 4-7 Promising co-classification links in the future

No.	IPC pairs	Description
1	B33Y, H01L	Convergence between the field of additive manufacturing and semiconductor devices
2	B33Y, B82Y	Convergence between the field of additive manufacturing and applications of nanostructures
3	B29C, C03C	Convergence between the field of shaping or joining of plastics and chemical composition of glasses, glazes, or vitreous enamels
4	B33Y, C23C	Convergence between the field of additive manufacturing and coating metallic material
5	B32B, G03F	Convergence between the field of layered products and photomechanical production of textured or patterned surfaces

To obtain more insights about the results and validate the accuracy of the proposed approach, real-life instances related to each promising convergence were investigated. Table 4-8 summarizes the results of the matching of promising convergence with new technologies that were searched from the articles published in journals or newspapers in 2017.

Firstly, as an instance of convergence between the field of additive manufacturing and semiconductor devices, a big progress in 3D printed electronics was found. Specifically, 3D printing of flexible circuits and sensor was presented by Optomec, a global supplier of 3D printed metals and electronics systems, at the international conference (“Optomec Showcases,” 2017). The Optomec engineer explained how circuits and sensors can be printed onto 3D and flexible substrates using various conductive metal and resistive materials with Aerosol Jet, a 3D printing tool. Optomec’s Aerosol Jet printing technology uses an additive manufacturing process that can print conductive, dielectric, and semiconductor inks onto a variety of 2D or 3D substrates. The company is accelerating the suggestion of 3D sensor solution technology for internet of things (IoT).

Secondly, there is an evidence of convergence between the field of additive manufacturing and applications/manufacture of nanostructure. Recently, a new technology to print complex nanostructures in various shapes and configurations using a carbon nanotube ink was developed by the engineers from the Korea Electrotechnology Research Institute (KERI) (Scott, 2017). This technology can be used to print electronic equipment that has sophisticated components. Furthermore, it is valuable in the manufacture of wearable electronics, which are getting progressively smaller but are still bulkier than many people’s preferences.

Thirdly, the convergence between the field of shaping or joining of plastics and chemical composition of glasses, glazes, or vitreous enamels was found in two instances. The research team at the Karlsruhe Institute of Technology (KIT) has developed a new way to 3D print glass objects with a material composed of glass powder suspended in a polymer resin (Kotz et al., 2017). The printed objects were then heated in an oven, where the polymer was burned away, leaving pure glass. According to the authors, their printing process is faster than traditional methods of glass production. Similarly, by using both plastic and ceramic as 3D printing materials, Autodesk created a casting mold for a new magnesium aircraft passenger seat frame, which is just as strong as a traditional one but much lighter (Clarke, 2017; Mearian, 2017). To produce a complex geometric model for a new seat frame, Autodesk used 3D design software and printed the 3D design in plastic resin first, in order to save money and time. Then that plastic frame was coated in ceramic material and heated to evaporate the plastic inside. With the resulting ceramic mold, the magnesium seat frame was manufactured by Aristo Cast, a Michigan foundry.

Fourthly, an evidence of convergence between the field of additive manufacturing and coating metallic material was found in Huang et al. (2017). In their work, a new method was developed to create 3D conductive structures with metal coatings on a flexible poly-di-methyl-siloxane (PDMS) substrate, which is commonly used for electronic applications. The proposed method can produce uniform metal coatings on 3D microstructures.

Lastly, the convergence between the field of layered products and photomechanical production of textured or patterned surfaces was expected by the sign of emergence and development of LCD-based stereolithography (SLA) 3D printer. For instance, SparkMaker is an LCD-based SLA 3D printer, where a LCD is used as a photomask instead of using laser or digital light processing (DLP) (White, 2017). This method can produce accurate 3D printing while reducing costs because it uses inexpensive LCD display to curing photosensitive resin layer by layer. In addition, Kudo3D's Bean 3D printer uses LCD panel coupled with a LED lamp to project slices of a 3D model onto a resin vat (Horsey, 2017). Both of them successfully reached their funding goal in a few minutes after launching on Kickstarter.

Table 4-8 Instances of prediction results

No.	Promising convergence	Instance in 2017
1	Convergence between the field of additive manufacturing and semiconductor devices	3D printing of flexible circuits and sensor ("Optomec Showcases," 2017)
2	Convergence between the field of additive manufacturing and applications of nanostructures	3D printing of nanostructure using carbon nanotube ink (Scott, 2017)
3	Convergence between the field of shaping or joining of plastics and chemical composition of glasses, glazes, or vitreous enamels	3D printing of glass objects (Kotz et al., 2017); Casting molds using 3D printed plastic with a ceramic coating (Clarke, 2017; Mearian, 2017)
4	Convergence between the field of additive manufacturing and coating metallic material	Selective metallic coating of 3D printed microstructures of flexible substrates (Huang et al., 2017)
5	Convergence between the field of layered products and photomechanical production of textured or patterned surfaces	LCD-based SLA 3D printer (White, 2017; Horsey, 2017)

4.5 Conclusion

In order to predict technological convergence in emerging technology, this study suggested a new approach, wherein patent co-classification analysis and link prediction are used considering multiple stages of emergence. In this study, various indices, including CN, Jaccard, PA, LP, Closeness product, and Betweenness product, were introduced to find a good feature for predicting technological convergence in different emergence stages. To illustrate the proposed approach, the case study of 3D printing technology was conducted with empirical patent data. With the empirical data, potential technology fields for technological convergence were found. Moreover, real instances for each predicted convergence were investigated to validate the results and provide richer insights. This case study demonstrated the applicability and usefulness of the proposed approach.

The proposed approach can be used to harvest useful insights on the technological convergence in emerging technologies. In addition, it can provide a useful framework for finding potential technological convergence in the future without assumption of past links (i.e. past convergence). Therefore, this approach can assist companies to search candidates for future technological convergence from various industries and to establish future strategies.

However, the proposed approach can be improved by analyzing more cases of emerging technologies in future research. With more cases, the more general implications would be obtained. Also, other network features and various time frames could be considered for the proposed approach to incorporate diverse characteristics of a network, and to provide a better prediction. Furthermore, the consideration of the direction of links, instead of undirected links, can allow an analysis of technological convergence from a flow perspective.

Chapter 5

Managing Dynamism in Complexity

5.1 Introduction

A feasibility study has played an important role as the first thing to be done before implementing and investing in technology-intensive and large-scale projects. A feasibility study is important in that it enables decision makers to obtain comprehensive information and results for the viability of an investment project (Jónsson, 2012). Thus, a feasibility study provides a basis for the decision on whether a project is to be implemented or not. Therefore, a feasibility study has been used to support a decision making regarding implementation and prioritization of projects. Especially, a feasibility study has been commonly applied to public investment projects, such as transportation, energy, power, water and sewage, and telecommunication infrastructure investments (Yun and Caldas, 2009; Ziara et al., 2002). For successful implementation of projects, a feasibility study usually considers various types of feasibility, including legal, marketing, technical and engineering, financial and economic, and social feasibility (Abou-Zeid et al., 2007).

Therefore, an expert-based analytic hierarchy process (AHP) is applied in a few feasibility studies to evaluate a project’s feasibility and determine a project's priority by considering multiple criteria of evaluation (Alidi, 1996; Dey 2001; Dey and Gupta, 2001; Lee and Park, 2011). However, the AHP-based feasibility study may result in a bias and inconsistency because of the nature of the AHP method (Yun and Caldas, 2009).

On the other hand, a feasibility study can be simply understood as an examination to determine the feasibility of investment alternatives by predicting costs and benefits for every alternative (Abou-Zeid et al., 2007). Traditionally, a cost-benefit analysis, which is a quantitative analysis, has been conducted for a feasibility analysis (Hutcheson, 1984; Shen et al., 2010; Yun and Caldas, 2009) because the two core elements that constitute a feasibility analysis are costs and benefits (Young, 1970).

In this context, recent public sector investment projects have had intense exposure to dynamic environments. The growth of the dynamic aspects of such investment projects can be explained in two parts: the dynamics of (1) a macro level (system level) and (2) a micro level (individual level). First, the dynamics of a macro level results from the fact that public investment projects have a range of potential effects. Because the ripple effects of public investment projects span not only the investment area but also external areas such as economic, social, and environmental (El-Sayegh, 2008; Katrin and Stefan, 2011), the macro elements that construct the benefits and costs, drawn from the investment projects, are diverse and react sensitively to environmental changes. Moreover, the elements of benefits and costs are interrelated in the macroscopic system, where the benefits and costs incurred by the project are formed. Second, the dynamics of a micro level results from the agents that participate in an investment project. The agents have a substantial impact on an investment project because they create a demand that significantly affects the feasibility of the project. Furthermore, these agents interact with one another, following their decision rules over time. This microscopic dynamics that the agents create influences the macroscopic system of project feasibility. Thus, it is difficult to predict the feasibility of a project regarding its macro and micro dynamics with an AHP-based analysis or a conventional cost-benefit analysis that usually ignores dynamism.

To overcome this limitation, there have been attempts to apply a single simulation method to deal with the dynamic complexity of feasibility analysis (Aldrete Sanchez et al., 2005; Cirillo et al., 2008; Conzelmann et al., 2005; Rode et al., 2001; Turek, 1995). However, such a method lacks the scope to cover the recent characteristics of public investment projects. For instance, Monte Carlo simulation does not reflect a change of system such as the feedback effect, system dynamics (SD) does not consider behavior at user level by focusing only on the dynamics of a system level, and an agent-based modeling (ABM) does not offer a systematic view and a causal relationship by focusing only on the dynamics of an individual level.

Nonetheless, a review of the literature on the simulation field reveals that various attempts to combine SD and ABM have been made to complement each simulation method (Figueredo and Aickelin, 2010; Größler et al., 2003; Kieckhäfer et al., 2009; Kim and Juhn, 1997; Schieritz and Größler, 2003; Vincenot et al., 2011). However, there has been no attempt to apply a combined SD and ABM method to feasibility analysis despite the complementary strengths that enable such an analysis to incorporate a dynamics of macroscopic system and microscopic individuals.

Therefore, this paper suggests a new approach for dynamic feasibility analysis that uses a combined SD model and AB model for public investment projects. The combination of SD model and AB model is proposed because of the dynamic aspects of the system and individual levels of public investment projects. The proposed model has the potential to analyze dynamic changes in the future and provide comprehensive information for project judges or policy makers. Furthermore, the proposed model is illustrated with a case study as an example of the model's practical use.

5.2 Feasibility Studies

5.2.1 Feasibility Studies for Large-scale Projects

The pre-investment phase of a project comprises several stages: the identification of investment opportunities; the analysis of project alternatives and preliminary project selection as well as project preparation (pre-feasibility and feasibility studies); and project appraisal and investment decisions (Abou-Zeid et al., 2007; Behrens and Hawranek, 1991). A feasibility study is the first and most important factor before undertaking project design and construction because the study's effectiveness directly affects the project's success. A feasibility study aims to objectively and rationally uncover the strengths and weaknesses of a proposed project, the opportunities and threats present in the environment, the resources required to complete the project, and ultimately the prospects for success (Justis and Kreigsmann, 1979).

A feasibility study for public investment typically considers the following types of feasibility: legal, marketing, technical and engineering, financial and economic, and social (Abou-Zeid et al., 2007). For instance, the Asian Bond Markets Initiative (ABMI) Group of Experts (2010) evaluated the feasibility of regional settlement intermediary (RSI) options for the Association of Southeast Asian Nations (ASEAN+3), especially for the following: pre-feasibility to select RSI options, operational feasibility to identify the scope of services of RSI options including interface functional blocks and service flows, legal feasibility to assess the extent of problem regulations or laws as "barriers" for each RSI option, and business feasibility to examine whether RSI options would be viable as commercial entities.

To incorporate the multiple components of feasibility, an expert-based AHP, a multi-attribute decision-making technique, is generally used as an analytical tool for a feasibility study (Alidi, 1996; Yun and Caldas, 2009). For example, Alidi (1996) proposed a methodology based on the AHP to measure the initial viability of projects and rank the priorities of projects. Dey (2001) used the AHP to suggest an integrated framework, which is incorporating technical, environmental, and social assessment, for project feasibility analysis. Dey and Gupta (2001) applied the AHP to select pipeline routes in a cross-country petroleum pipeline project. Lee and Park (2011) applied the AHP to assess the feasibility of Korea National R&D program.

In simple terms, the two core criteria used to judge feasibility are required cost and value to be attained (Young, 1970). Traditionally, cost-benefit analysis has been utilized for the feasibility analysis of public sector investment projects (Shen et. al., 2010; Yun and Caldas, 2009). Since cost-benefit analysis focuses only on final output represented as net present value (NPV), there are several methods that consider NPV changes in order to support conventional cost-benefit analysis.

5.2.2 Dynamic Approach in Feasibility Study

There have been a few organizational projects and academic investigations that use and explain feasibility analysis by a single simulation method. For example, Jacques Cartier and Champlain Bridges Incorporated (JCCBI) (2011) in Canada implemented a pre-feasibility study concerning the replacement of the existing Champlain Bridge and utilized the simulation for evaluating future travel demands (flows) according to scenarios of additional bridges. The ABMI Group of Experts (2010) used a simulation for predicting revenue-side cash flows and included such variables as market share, revenue, running cost, and start-up cost according to scenarios for legal environmental change. The New South Wales (NSW) Department of Environment, Climate Change and Water (2010) used a pre-feasibility study for solar power precincts in Australia and conducted a simulation to estimate electricity generation for each precinct. A UCTE-IPS/UPS study (2008) carried out a feasibility study on the synchronous interconnection of the countries of the Commonwealth of Independent States and the Baltic States (IPS/UPS) and the Union for the Co-ordination of Transmission of Electricity (UCTE). The study modeled low flows for steady state and dynamic system simulations, and analyzed a dynamic change of power capacity in a synchronized system and the effect of synchronous coupling and transient stability. However, the study did not provide detailed explanations of specific simulation methods.

Other cases have offered specific methodology. Aldrete Sanchez et al. (2005) developed a feasibility evaluation model for toll highways based on Monte Carlo simulation that derived the probability distribution for the development cost of toll highways and analyzed financial feasibility and risk. Rode et al. (2001) suggested Monte Carlo methods for the appraisal and valuation of a nuclear power plant. They insisted that the valuation of large-scale technology-based projects such as power plants should incorporate political, technological, and economic risks, and that Monte Carlo simulation is effective in this task. Similarly, Turek (1995) suggested a SD model to analyze the impact of resource constraint because of social factors, political factors, and information on the long-term financial performance and safety of a nuclear power plant. These studies only simulated system interactions at macro level and did not consider the individual level.

The European Union (EU) Transport Corridor Europe-Caucasus-Asia (TRACECA) program (2008) studied the feasibility of the development of maritime transport links in the Black Sea region. The program developed a trade model using ABM to forecast the evolution of trade flows (import and export) in the region. As a result, countries were modeled as autonomous individuals that had their own variables and behavior, and that existed as separate entities within the system. Elsewhere, a research group from the Argonne National Laboratory developed the electricity market complex adaptive system (EMCAS), a software, to model and simulate the electricity market and its decision structures, and defined heterogeneous companies, regulators, physical elements, etc. as agents (Cirillo et al., 2008; Conzelmann et al., 2005). The research group had the advantage of considering the macro environment and micro-elements together by operating multi-dimensional interaction layers (i.e. regulatory, business, and physical layers). However, the study specialized in the general-purpose electricity market and did not conduct a feasibility study, even though the software tool can support issues similar to a feasibility study by providing the framework to conduct experiments for the potential effects of various elements on the costs and benefits of an electricity system.

The approaches to dynamic evaluation for a feasibility analysis are very limited. In particular, the attempt to apply a simulation technique directly to the dynamic evaluation of economic feasibility is rarely found in the public investment project area. Prior practical studies were limited in that they utilized conventional simulation models in order to predict and evaluate only partial information, such as market shares and sizes, static or dynamic technical validity, and expected technical impacts. They did not actively set economic feasibility as the determinant target variable and did not engage with the comprehensive dynamic nature of investment projects.

5.3 Research Process

5.3.1 Conceptual Framework

To incorporate the dynamic aspects of agents and the system of technology-intensive and large-scale projects into a feasibility analysis, this research combines a SD model and an AB model to model each system and individual level of a project. For such a purpose, the conceptual framework is generated based on the structure that is suggested by Sterman (2000) as the general structure of a model when agents exist in the system. As shown in Figure 5-1, the conceptual framework for the proposed model consists of two parts: (1) the structure of the system for feasibility analysis and (2) the decision rules of the agents.

This framework is similar to the structure suggested by Sterman (2000) in that it distinguishes the decision process of the agents from the institutional structure of a model and represents an information feedback system. However, the difference is that in this framework, the agents' decisions are considered outcomes of their emergent behavior, which is hardly predictable with SD approach because they utilize the information from the system and themselves in their decision-making with a high degree of heterogeneity.

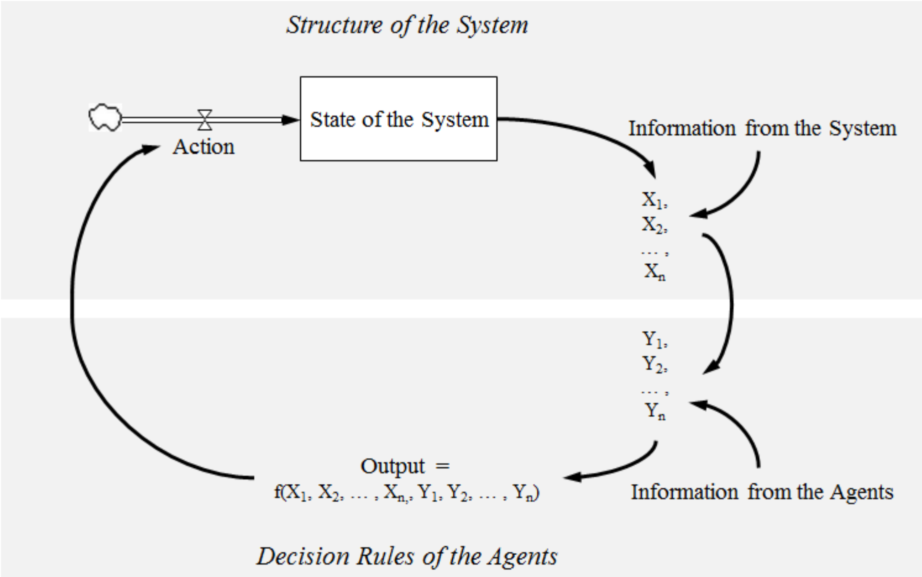

Figure 5-1 Conceptual framework of dynamic feasibility analysis

Specifically, among the various types of feasibility, such as technological feasibility and political feasibility, we focus on economic feasibility, which is widely used in public investment and assessed by a cost-benefit analysis. Here, costs and benefits are formed by numerous elements and variables; moreover, there are complex causal relationships between the elements and variables. In particular, the behavior of agents that participate in the project is the most important element because it significantly affects benefits. However, behavior emerges from diverse factors and is therefore difficult to predict.

In sum, the conceptual framework considers two main parts for feasibility analysis. The first conceptual part, the structure of the system, is modeled as a SD model, and the second part, the decision rules of the agents, is modeled using an AB model; thus, each part can be depicted appropriately. The structure of the system, the first conceptual part, contains the overall process for assessing feasibility and generates the information that will transfer to the participating agents. The agents absorb the information from the system and from themselves and utilize it for their decisions in the second part, the decision process of the agents. The decisions, the outcome of decision rules, become action that changes the state of the system and consequently alters the information from the system that will be passed to the agents. The cycle of information exchange between the two parts continues in the process of estimating project feasibility. In addition, the process of exchanging information between the two parts is embodied in the model through combining the SD model and the AB model in an integrated model.

5.3.2 Composition of Modules

On the basis of the conceptual framework, a combined SD model and AB model for dynamic feasibility analysis is composed of eight modules, which are agent, stock, input, intermediate, benefit, cost, feasibility, and event. Descriptions of the modules are presented in Table 5-1.

Table 5-1 Description of modules in combined model

Module	**Component**	**Description**	**Type of model to which it belongs**
Agent		People who potentially use and participate in the object of the technology-intensive and large-scale project and their behavior	AB
Stock		The state changes, and the amount of certain type of users that should be considered	SD and AB (Overlapped)

Input		The predefined variables according to the specific characteristics of the project	SD and AB (Overlapped)
Intermediate		The intermediate variables for computing benefits and costs	SD and AB (Overlapped)
Benefit	Total benefit	Total benefit	SD
	Benefit element	Components of total benefit	
Cost	Total cost	Total cost	SD
	Cost element	Components of total cost	
Feasibility	NPV	Net present value	SD
	BC ratio	A ratio of the benefits relative to its costs when the benefits and costs are expressed in discounted present values in monetary term	
Event		The event that is happening in the future	SD and AB (Overlapped)

The agent module represents people who potentially use and participate in the object that takes the form of a technology-intensive and large-scale project. For example, a driver can be an agent in a bridge construction project and a household or a power plant can be an agent in a water/electricity resources-related project. The agent module also implies that users behave according to their decision rules and heterogeneity, although who the agents are and which decision process they adopt depend on the properties of the project.

The stock module represents the users' changes of state and the amounts of certain types of user that should be considered when evaluating feasibility. The module plays the same role as in single SD modeling because it represents entities that accumulate or deplete over time. However, in this research, and unlike single SD modeling, the rate of change in a stock module is determined by user behavior. The traffic in the aforementioned bridge construction project and the demand for water/electricity in the resources-related project are examples of stock modules.

The input module is referred to as the given parameters. The variables that are initially defined according to the specific characteristics of the investment project belong to this module. For example, the length or capacity of a road in the bridge construction project, and the ratio of households to a power plant or the price of water/electricity in the resources-related project can be parts of input modules. All the other intermediate variables, which are placed in the costs and benefits calculation process and consequently altered by the other variables, such as the velocity of a car on the bridge and consumer surplus in the water/electricity market, belong to the intermediate module.

The benefit module and the cost module are two core components for economic feasibility. Each module usually has several elements that constitute the total benefit or cost. For example, the benefit of bridge construction can include reductions of travel time and vehicle operating time. The benefit of the water resources project, especially a multipurpose dam construction, can be composed of the supply of water for living/industrial use and flood control. Generally, the total cost of the project mainly consists of construction, incidental, compensation, maintenance, and extra costs. Some elements of benefit and cost can have predetermined and fixed values similar to the input module, while others can be obtained by interacting with other modules such as input, intermediate, and stock.

Based on the total benefit and total cost, the NPV and benefit-cost

(BC) ratio are computed over time and are the two components that determine the feasibility module. Here, all benefits and costs are expressed in discounted present values in monetary terms. The BC ratio represents the ratio of the benefits of a project relative to its costs.

The last module is the event module. The objective of this module is to reflect future events. The event module plays the most important role in scenario analysis. The scenarios themselves can be constructed to reflect reality. Policy or other situations, which are expected to influence how the agent behaves and how feasibility is derived, can also be depicted as scenarios and modeled as event modules.

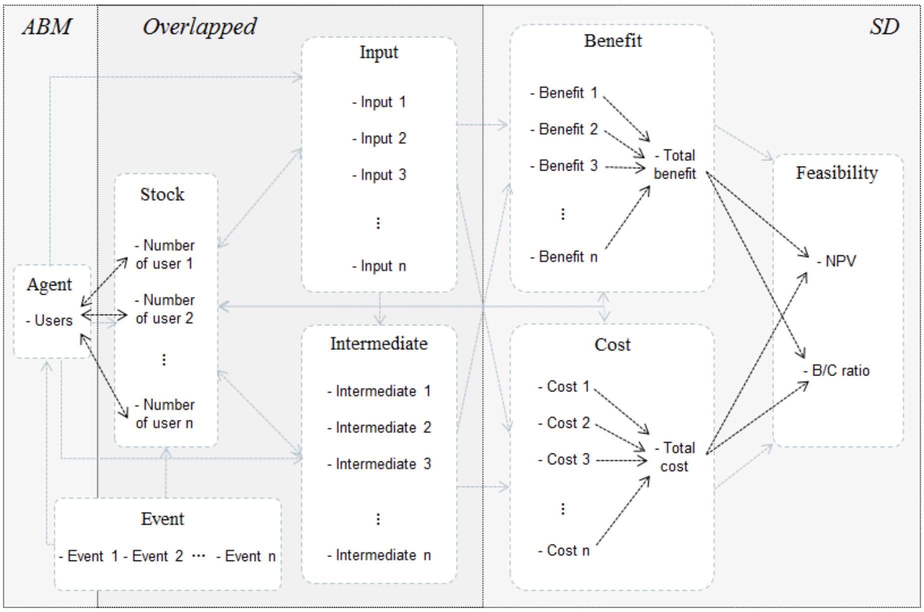

Figure 5-2 Composition of modules in combined model

Each module belongs to either/both the SD model or/and AB model and interacts in the model or across the model. As shown in Figure 5-2, the SD model embraces all modules except the agent module because it models the whole system structure in order to assess feasibility. In particular, the agent module is significantly associated with the agents' decision rules while other modules mainly constitute the system structure. Hence, to model the system structure, a SD model is established through the predefined causal relationship among the variables in all the modules except the agent module. On the other hand, an AB model encompasses the agent, stock, input, intermediate, and event modules, which are related to agents' decision-making. The core module in an AB model is the agent module because determining agents who are involved in the project and making decisions, which will affect the project's feasibility, should first be considered in order to develop the agents' decision rules. Then, the variables that influence the agents' decisions are considered. Usually, these variables belong to the stock, input, intermediate, and event modules, and consequently the agent module interacts with these modules.

Because the SD model and the AB model encompass some of the same modules, there are overlaps among stock, input, intermediate, and event modules. These modules conceptually represent a link between the SD model and the AB model and reflect that there are partially or wholly shared parts in the modules due to the interactions between the outputs and the inputs of the SD model and the AB model. Specifically, the overlap between the two models occurs where the outputs of the SD model are used as the inputs of the AB model; similarly, the outputs of the AB model are used as inputs of the SD model. In addition, from the beginning, some components remain common to both the SD model and the AB model and are therefore also considered an overlap. However, the core modules and variables that link the SD model and the AB model vary depending on the project.

5.3.3 Overall Process

To depict the system- and individual-levels in feasibility analysis, this study suggests using a combined SD and ABM approach, thereby supporting the conceptual framework. The overall process for the dynamic feasibility analysis with the proposed approach is shown in Figure 5-3. The process consists of five steps: identification of the variables, modeling of the system/individual level, combining a SD model and an AB model, a simulation with scenario analysis, and interpretation of the simulation results.

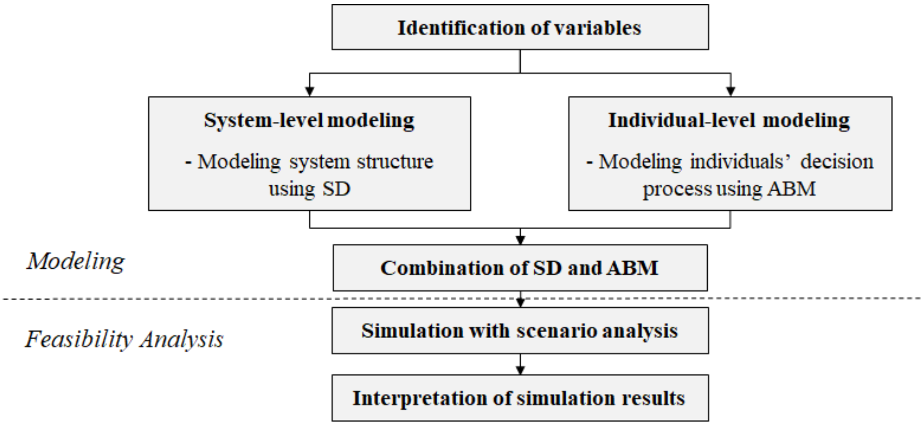

Figure 5-3 Overall process for dynamic feasibility analysis

The first stage of the process is to identify the variables in each module that should be considered in the feasibility study depending on the type of project. For example, in the bridge construction project, the benefits can consist of the reductions of travel time and vehicle operating time, while in the water resources project, the benefits are the supply of water for living/industrial use and flood control. Consequently, the variables related to the feasibility of each project are different from each other and should therefore be identified at the first stage.

The second stage is to model the system structure and the agents' decision rules at system-level and individual-level respectively. The interactive modules in the system structure for feasibility analysis, such as stock, input, intermediate, benefit, cost, feasibility, and event modules, are modeled using SD. A SD model can vary according to the structure or method of calculating benefits and costs. Hence, the specific relation between the components and their variables should be predefined. Second, the dynamics emerging from individuals are modeled using ABM. Once the agent is defined, his or her decision process is described through the agent’s state and decision criteria. An AB model can also be altered depending on the agents or the decision criteria that we focus on.

The third stage is to combine the SD model and AB model into an integrated model through an overlap between the models, as addressed in Section 5.3.2. The overlap between the models can be observed when one uses the outcome of the other as its input or when they both use the same component from the beginning. Therefore, the core modules and variables that link the two models vary depending on the project. The way in which the SD model and AB model are intertwined with one another also varies.

Finally, in the fourth and fifth stages, the combined model for feasibility analysis is simulated using various conditions and scenarios. A synthesis diagnosis of the feasibility analysis of the investment project is then obtained based on the results of the simulations. The proposed model delivers results that incorporate macro- and micro-impacts that occur in the scenarios. In addition, within the scenarios, the range of multiple variables can be tested; therefore, multifaceted analysis is possible in accordance with the interests of project judges or policy makers. In this way, more comprehensive and useful information on the feasibility of the project is acquired from the simulation results using diverse scenarios and conditions. Then, the dynamic feasibility analysis of the project is complete.

5.4 Evaluation of Large-scale Project

5.4.1 Background

A feasibility analysis on a bridge construction project has been conducted by comparing the associated costs and resulting benefits with their diverse elements (Korea Development Institute (KDI), 2008). For instance, the costs include construction, incidental, and compensation costs, and the benefits consist of reductions in vehicle operating cost, travel time, accidents, and air pollution cost, which are estimated based on traffic. Here, most elements are not independent of each other. Instead, they influence one another, which leads to complex causal relationships in the system. Furthermore, when it comes to benefits in particular, the behavior of drivers that emerges from their own decision rules and creates the traffic is a very important factor. This is because the emergent behavior of drivers affects the benefits and consequently the feasibility of the project. In addition, behavior is intertwined with the system because the drivers make decisions using system information such as real-time traffic information. The result of the drivers' behavior also influences the state of the system.

In this situation, SD is appropriate to model the whole system structure because of the complicated causal relationships. On the other hand, ABM rather than SD is better at depicting the emergent behavior of drivers through intuitive modeling of the agents' decision rules. Moreover, a combined approach of SD and ABM is suitable in order to incorporate the interactions between the system structure and the drivers' decision rules. Consequently, an illustrative case study of a bridge construction has been conducted to examine how the proposed model can be applied in practice.

5.4.2 Modeling Process

1) Identification of Variables in Modules

To simplify the case study of a bridge construction project, we established a situation whereby one bridge already connects two regions and an additional bridge is being considered. With regard to such a bridge construction project, the general modules from the proposed combined SD model and AB model take concrete shape in accordance with the characteristics of the project as shown in Figure 5-4. For the purpose of practical investigation, this study follows the guidelines from the KDI (2008) for feasibility studies for road and railroad projects, in which bridge construction is included, in order to specify the components and variables that constitute the basic modules and the relationships among them.

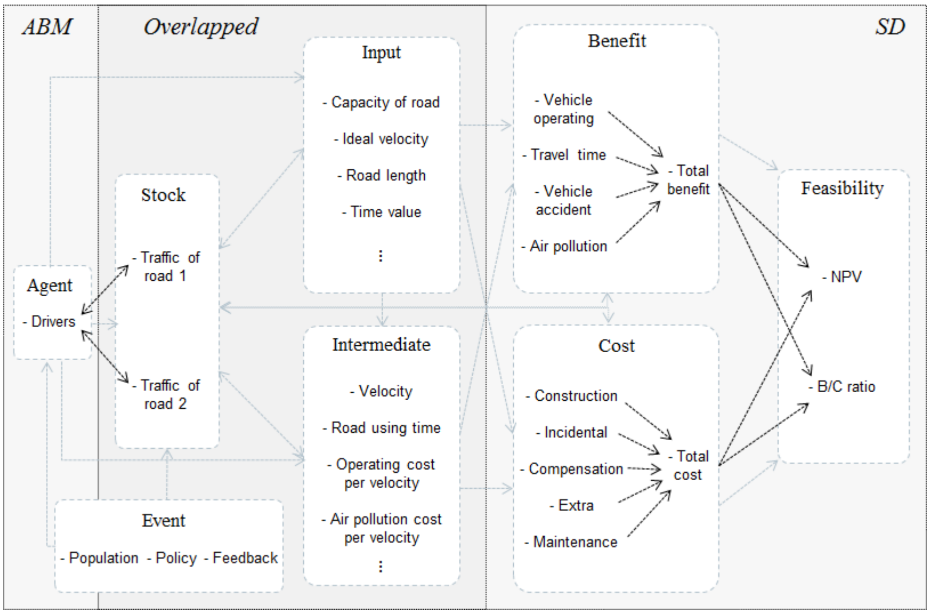

Figure 5-4 Composition of modules and variables in case study

Specifically, according to the KDI guidelines, the feasibility of a road project is assessed by estimating the benefits and costs. The benefits are obtained from reductions in vehicle operating cost, travel time, accident cost, and air pollution cost, and the costs are estimated by combining construction, incidental, compensation, maintenance, and extra costs. On this basis, the total benefit in the benefit module has four elements and the total cost in the cost module has five elements.

In addition, based on the formulas of each element of the benefits and costs from the guidelines, the necessary variables are identified. These constitute the input and intermediate modules according to whether or not they are initially defined. For example, the capacity of a road, ideal velocity, road length, and time value are assumed in advance to be certain values that are not affected by the other variables. Therefore, they compose the input module. The intermediate module incorporates variables such as velocity, road-using time (time spent on the road), operating cost per velocity, and air pollution cost per velocity, which cannot be determined before the other related variables are provided.

In addition, the velocity of a car and road-using time (time spent on the road) are calculated based on traffic, and the amount of traffic is determined by the number of drivers who currently use the road. Accordingly, the stock module consists of several stocks that represent the traffic of each road or region that arises from the behavior of drivers. The agent module represents drivers who potentially/actually use an existing road or a new road and their behavior. Consequently, the real-time traffic of each road or region, detected from each stock, fluctuates according to the rate of change in the states of drivers from the agent module.

Lastly, the event module is composed of three events that reflect the impacts of increases in traffic that result from population growth, regional development policy, and feedback from the bridge construction.

2) Modeling of the System Level: SD Model

The primary purpose of the SD model is to capture the system structure, calculate the final benefits and costs on the basis of real-time traffic estimated through the AB model, and finally to compute the indicators of economic feasibility such as the NPV and the BC ratio. For such purposes, the SD model covers stock, input, intermediate, benefit, cost, feasibility, and event modules, which are all the modules except for the agent module.

In the SD model, as shown in Figure 5-5, two parts representing the situation before and after construction are modeled because the project's benefits, as previously described, are calculated through reduced costs before and after construction. In other words, because the benefits are calculated by subtracting the costs incurred after construction from the costs generated before construction, two parts are modeled. However, regardless of the part, each module and variable play the same role, and the only difference between the two parts is the number of alternative roads.

Specifically, based on the guidelines from the KDI, there are four elements in the total benefit. The first element is reduced vehicle operating cost. This element is calculated through differences in vehicle operating cost incurred after and before construction. Vehicle operating cost is computed by using the operating cost per road length per car depending on velocity multiplied by road length and total traffic. The second element is the reduced travel time cost that results from construction. Travel time cost is calculated by multiplying road-using time (time spent on the road) by time value per car and total traffic. The third element is reduced accident cost; and the accident cost is derived through the following equation: ((number of traffic accidents/deaths per road length per car*accidents/deaths cost + amount of property damage per road length per car *property damage cost)*road length*total traffic). The last element is reduced air pollution cost; and the air pollution cost is calculated by air pollution cost per road length per car depending on velocity multiplied by road length and total traffic. All these relationships among each element of the benefits and the variables are represented as arrows in a stock-and-flow diagram of the SD model.

Among the variables that compose the benefit elements, road length, time value, number of traffic accidents/deaths per road length per car, amount of property damage per road length per car, accidents/deaths cost, and property damage cost are not related to the amount of traffic and thus have constant value. However, the other variables such as the velocity of a car and road-using time change over time according to the traffic of a road. Therefore, these variables are linked to the stocks that represent the traffic of each road, where the real-time traffic of each road is detected from the AB model. Furthermore, the velocity of a car according to the traffic is derived by the equation that was developed by the U.S. Bureau of Public Roads (BPR), based on the guidelines from the KDI. When the velocity is calculated, the operating cost per velocity and air pollution cost per velocity are derived through tables used in the KDI guidelines, where the tables represent operating cost and air pollution cost per velocity. Moreover, road-using time is computed as the road length divided by velocity.

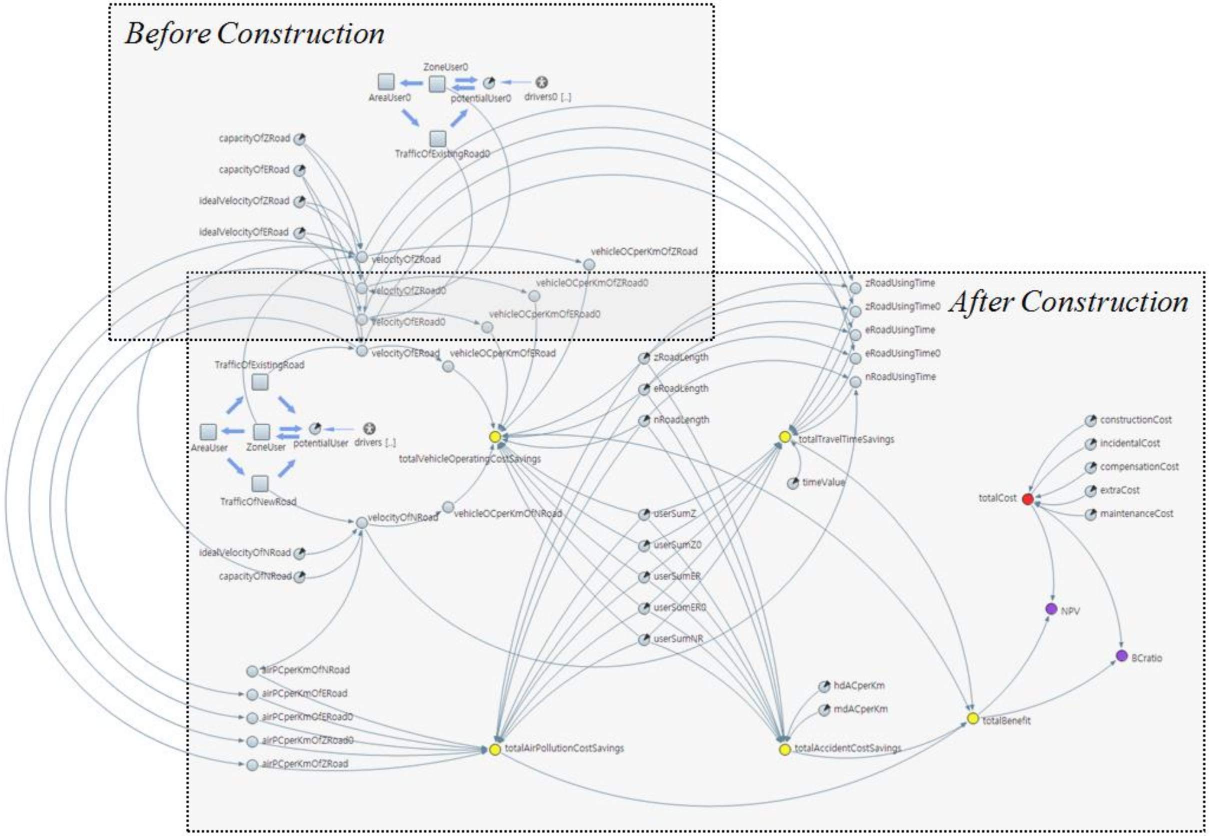

Figure 5-5 SD model for dynamic feasibility analysis in case study

In addition, there are five elements, in the total cost based on the KDI guidelines. Among these elements, construction, incidental, compensation, and extra costs are assumed to be incurred once at the point of the opening of a bridge, and maintenance cost is assumed to be incurred every year once a bridge has been constructed. Finally, every element of the costs and benefits is converted to discounted present value. Then, the NPV and the BC ratio are computed based on the discounted total cost and total benefit.

3) Modeling of the Individual Level: AB Model

The AB model covers agent, stock, input, intermediate, and event modules and primarily aims to estimate real-time traffic through modeling drivers' behavior with regard to road decisions. In the AB model, there are two parts: (1) entering and (2) the decision stage. At the entering stage, drivers determine the traffic of regions as they move from the outside regions to the regions surrounding the two bridges, and from the surrounding regions to the entrance regions of the bridges. Here, each state of the drivers during the entering stage is modeled as shown in Figure 5-6. Specifically, drivers in the outside regions are defined as *potential users*. As they move into the surrounding regions of the two bridges, they become *zone users*. Finally, if they reach the entrance regions of the bridges they become *area users*. The rate of flow from *potential users* to *zone users* is determined by the parameter, *zone user rate,* and the rate of flow from *zone users* to *area users* is determined by *area user rate.* Once the drivers become *area users*, they are supposed to enter the decision stage where they must choose between two roads, an existing and a new road, based on their decision rules.

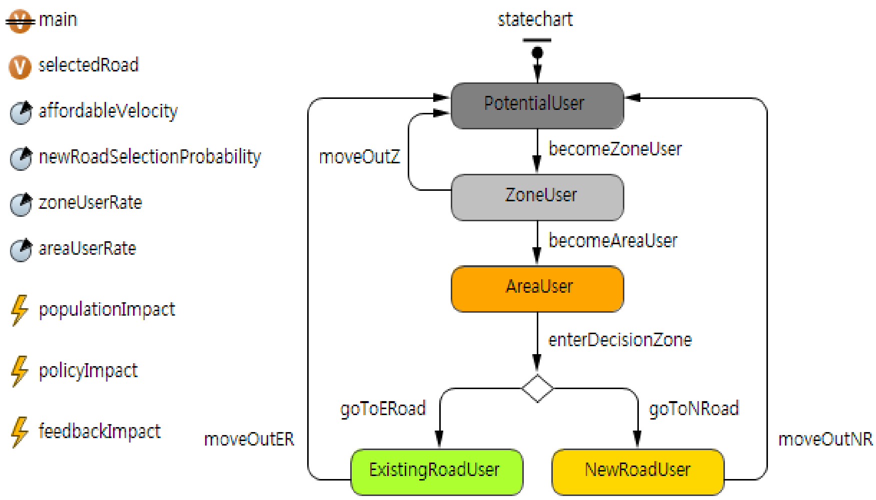

Figure 5-6 State diagram for agents in AB model

The decision process of each driver mainly considers two factors: traffic and intimacy. Based on the assumption that a new road has bigger capacity and ensures higher velocity, we propose a scenario whereby a driver considers using a new road as a priority, unless there is too much traffic. If the velocity of a car on the new road is lower than the driver's affordable velocity, where each driver has his or her own affordable velocity, drivers would take the existing road instead. Similarly, drivers evaluate the existing road by comparing their affordable velocity with the velocity of other cars on the existing road, which is determined by the traffic of this road. Meanwhile, drivers' choice is also affected by the intimacy of a road. Even though there is not much traffic on the new road, a certain level of traffic on the existing road is maintained because of its higher intimacy. In this model, the levels of intimacy of the existing and new roads are considered through introducing a parameter, *new road selection probability*, which reflects the possibility of preferring a new road and differs according to each driver. By comparing the possibility of selecting a new road with the assumed level, drivers are arranged into two groups where one represents a person who is willing to select a new road while the other represents a person who is not. Finally, the traffic of each road is decided upon after considering all the decision processes of each driver.

4) Combining the SD Model and the AB Model

For a comprehensive analysis of a dynamic feasibility assessment system, the SD model and the AB model are combined into a single model based on the overlapped modules. As introduced in Section 5.3.2, the SD model and the AB model share stock, input, intermediate, and event modules. Among these modules, in this case study, a core module that intertwines the SD model and the AB model is the stock. In addition, the core variable is the velocity, which is derived from the stock module and included in the intermediate module.

Once the result of each driver's state and the road that has been selected are drawn from the AB model, the overall results cause varying traffic in each region and each road in the stock module that belongs to the combined SD model and AB model. Then, in the SD model, the traffic determines the speed of a car in each road, depending on the parameters of the capacity of the road and the ideal velocity in the input module. Subsequently, the velocity of a car in each road is transferred to the AB model and used for the driver's decision rule. In this way, the two models become an integrated model that interacts. The output of the AB model is used as the input of the SD model and then the output of the SD model is used as the input of the AB model on the premise that drivers can receive real-time traffic information and that the traffic is used as a key variable in determining the road.

5) Scenario Analysis

This study aims to suggest a dynamic feasibility analysis and illustrate a process of analysis rather than obtain accurate results from scenario analysis. Hence, a basic scenario composed of certain assumptions, and not exact parameters, was constructed, and the other scenarios, such as population growth, regional development policy, and feedback, were developed through altering some part of the assumptions from a basic scenario.

For a basic scenario, it is assumed that the number of *potential users* is 10,000, 50% of whom become *zone users*, and that 20% of *zone users* become *area users*. The variables such as ideal velocity and capacity of a road are assumed on the basis of a one-lane road in a metropolitan city in accordance with the guidelines of the KDI. The maintenance cost is assumed based on a standard maintenance and administrative cost of a general national road and the other costs are assumed in consideration of the number of users. Table 5-2 summarizes the initial values of major variables set for basic scenario (See the Appendix F for information about overall variables and their data/assumptions).

Table 5-2 Initial value of major variables for basic scenario

Name of variable	**Units**	**Definition**	**Initial value**
Potential user	n/a	Driver in the outside regions of the bridges	10,000
Zone user	n/a	Driver in the surrounding regions of the bridges	50,000
Area user	n/a	Driver in the entrance regions of the bridges	1,000
Affordable velocity	km/hr	Marginal range of velocity a driver will tolerate	uniform(50,70)

New road selection probability	%	Probability of selecting a new road, which represents a degree of progressive tendency	uniform(0,1)
Capacity of road	n/a	Capacity of an existing/new road per hour	Existing road: 400 New road: 625
Ideal velocity	km/hr	Ideal velocity of an existing/new road	Existing road: 60 New road: 80
Velocity of road	km/hr	Actual velocity of an existing road: Velocity of road = Ideal velocity* (Capacity of road / (Capacity of road + Traffic of road))	Ideal velocity
Road length	km	Length of an existing/new road	Existing road: 100 New road: 80
User sum	n/a	Number of users	0
Time value	₩/hr	Time value per car	14,990
Construction cost	₩	Construction cost	4,000,000,000
Incidental cost	₩	Incidental cost	200,000,000
Compensation cost	₩	Compensation cost	100,000,000
Extra cost	₩	Extra cost	200,000,000
Maintenance cost	₩/day	Maintenance cost	255,000
Vehicle operating cost (OC) per km according to velocity lookup table	n/a	Vehicle operating cost per km classified by velocity	Velocity (km/hr) / Cost (₩/km): 10 / 332.99 20 / 267.75 30 / 232.72 40 / 202.16 50 / 183.63 60 / 174.48 70 / 168.82 80 / 161.19 90 / 159.28 100 / 160.12 110 / 162.53 120 / 167.36

			Velocity (km/hr)	Cost (₩/km)
Air pollution cost per km according to velocity lookup table	n/a	Air pollution cost per km classified by velocity	10	67.57
			20	34.38
			30	23.68
			40	18.32
			50	15.11
			60	12.96
			70	11.39
			80	10.21
			90	9.29
			100	8.54

To reflect the changes in feasibility in response to future environmental changes, additional scenarios for population growth, regional development policy, and positive feedback were configured along with a basic scenario. Each scenario was developed as a parameter variation of a basic scenario with the help of the event module. Specifically, a population growth scenario represents an increase in the number of users that results from natural population growth. Here, an average annual growth rate is assumed as 1%, and the numbers of *zone* and *area users* increase accordingly. A regional development policy scenario reflects an increase in traffic in the immediate area of the bridge that is caused by regional development policies such as new town construction, relocation of government agencies, and development of a tourist location. In this scenario, traffic in the zone and immediate areas is assumed to increase by 10% after the three years since bridge construction. Lastly, a feedback scenario indicates that the flow of traffic from other regions increases because the local economy is vitalized in accordance with improved accessibility to the region that results from the construction of a bridge. For this scenario, the number of *area users* is assumed to increase annually in proportion to the number of users who select the new road.

5.4.3 Results

1) Results of the Basic Scenario

First, according to the assumptions for a basic scenario, the integrated model for a dynamic feasibility analysis of the bridge construction project was simulated over a ten-year period.

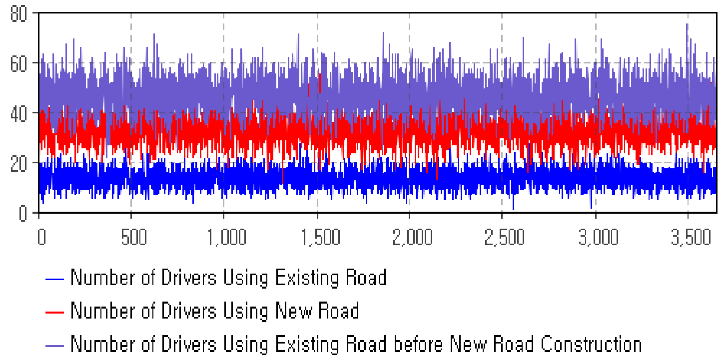

Figure 5-7 Average daily traffic of each road in basic scenario

Figure 5-7 shows the average daily traffic of each road. This fluctuates over time depending on the status of drivers in the AB model that results from the interaction with the SD model. As shown, the average traffic of the new road, which is colored red, is about one-and-a-half times the average daily traffic of the existing road. Furthermore, the feasibility of the project is ensured after about six years, and over ten years, the NPV reaches about 1.8 billion won (about US $1.6 million) and the BC ratio becomes about 1.3.

Moreover, in the basic scenario, a sensitivity analysis was performed through varying the initial value of the parameters, such as capacity of the road and ideal velocity, in order to examine the changes in the NPV and BC ratio. As a result, when the initial road capacity is changed, the final NPV and BC ratio increase as the initial road capacity increases. This result indicates that the total benefit increases in accordance with increases in the velocity of a car because as the road capacity becomes greater, more traffic can be handled.

In addition, when the initial ideal velocity is changed at 1000 days, it is observed that the final NPV and BC ratio increase rapidly as the differences between the ideal velocity of a new and an existing road become bigger

2) Comparison of Scenarios

Second, the integrated model for dynamic feasibility analysis of the bridge construction project was simulated over a ten-year period according to four scenarios: the basic, population growth (scenario A), regional development policy (scenario B), and positive feedback (scenario C). The results of the four scenarios are compared in terms of the final NPV and BC ratio ten years hence, and turnaround time.

Compared to the basic scenario, the other three scenarios create an early surplus, and the final NPVs and BC ratios of them increase. In particular, scenario C, which represents the vitalization of a local economy caused by the construction of a bridge, results in a rapid increase in the final NPV and BC ratio compared to the other scenarios. It is possible to guess that the reason is that, in scenario C, the *area users* in the AB model increase considerably more than in the other scenarios because as the number of *area users* increases, the number of *area users* who select a new road will increase, and then the number of *area users* will increase again in proportion to that in accordance with our assumption. This positive feedback effect on the number of *area* *users* in the AB model can result in substantial growth in the final NPV and BC ratio.

Specifically, in scenario A, the feasibility of the project is guaranteed after about five years, down from six years in the basic scenario. Moreover, ten years later, the NPV is about 3.3 billion won (about US $3 million), up from 2 billion won (about US $1.8 million), and the BC ratio becomes about 1.5. With regard to scenario B, the project begins its turnaround about four-and-a-half years later, which is about 400 days less than the original. In addition, the NPV is about 3.6 billion won (about US $3.3 million), 1.6 billion won (about US $1.5 million) higher than the original, and the BC ratio becomes about 1.6 after ten years. Lastly, the result of scenario C shows that the project is expected to show a profit after about four years, and after ten years, the NPV is about 6.4 billion won (about US $5.8 million) and the BC ratio becomes about 2.1, the highest value among the scenarios.

5.5 Discussion

5.5.1 Theoretical and Practical Implications

To support a feasibility analysis of technology-intensive and large-scale projects in a dynamic environment, an integrated approach using SD and ABM was suggested in this study. In the proposed approach, SD was used to model the system structure for feasibility analysis while ABM was used to depict the heterogeneous agents' behavior. The illustrative case study of a bridge construction was conducted to present how the proposed approach can be used for a practical feasibility analysis.

In sum, the results of the case study imply that the various factors in the present and the future can have a significant effect on the final feasibility measures because of the dynamic aspects of the project both at the system and the individual levels. Thereby the results indicate the importance for the feasibility analysis to consider such dynamic aspects and diverse scenarios. Moreover, the results demonstrate that the proposed model, with its integrated approach, has the potential to analyze dynamic changes in the future and provide comprehensive and useful information for project judges or policy makers in advance. Furthermore, the proposed approach is expected to provide a robust framework that can be applied to a wide range of investment projects.

Specifically, the results of a basic scenario and a sensitivity analysis, which have been described in 5.3.1, show that the changes in parameters in the SD model can cause critical differences in the final feasibility measures. These significant changes in the final feasibility measures emerge from the interactions between the SD model, which depicts the macroscopic system, and the AB model, which captures the individual behavior. In other words, through the proposed approach, the impact of the changes in system elements on the project feasibility can be estimated by simultaneously considering the system level, individual level, and their interactions. Because various settings can be easily analyzed and depicted with the help of the proposed model, project judges or policy makers can consider diverse situation in a short time.

In addition, the results of the four scenarios, which have been described in 5.3.2, show that the changes in parameters in the AB model can make significant differences in the final feasibility measures. Therefore, the impact of the changes in the individual level on the project feasibility can be appropriately analyzed through the proposed approach by considering the system level, individual level, and their interactions. Moreover, these four scenario analysis show that the event, such as a change in policy, that may occur in the future can be easily simulated through the proposed model.

5.5.2 Generalization

Furthermore, other projects, instead of a bridge construction project, can be considered through the proposed approach by considering their characteristics regarding system and individual level. Specifically, as shown in Table 5-3, projects can be classified into four categories by whether an agent exists in a project and affects the project feasibility, and whether a method of calculating benefits and costs is standardized.

Table 5-3 General types of projects and model guidelines

General type	Agent	Standardized formula	Example	How to model
1	○	○	Bridge construction projects, water resource-related projects	Construct both a SD model and an AB model; specify the modules in a SD model by the standardized formula for feasibility
2	○	X	-	Construct both a SD model and an AB model; specify the modules in a SD model by the experts of a survey
3	X	○	-	Do not need an AB model; specify the modules in a SD model by the standardized formula for feasibility
4	X	X	R&D projects	Do not need an AB model; specify the modules in a SD model by the experts of a survey

A bridge construction project is an example of a project that have agents and standardized methods of calculating benefits and costs. In such projects, both a SD model and an AB model are constructed and moreover, the modules in a SD model are specified by the standardized calculation methods of feasibility. A water resource-related project is also included in this type of projects, where the agent can be a household or a power plant and the calculation methods of feasibility is standardized. On the other hand, a project that has no agents and no standardized calculation methods of feasibility does not need an AB model, and the modules in a SD model can be specified by the experts or a survey. For instance, generally, a R&D project has no specific agent, and the calculation method of feasibility is defined depending on the characteristics of a projects. Similarly, the proposed model can be applied to a project that has an agent and unstandardized calculation methods or a project that has no agent and standardized calculation methods as well. However, the details of a SD model, an AB model, and an integration process should be specified and developed depending on the project with an in-depth consideration.

5.6 Conclusion

In this paper, in order to analyze the feasibility of technology-intensive and large-scale projects, we suggested a combined SD and ABM approach, where the SD model depicts the relationships among components that shape the benefits and costs of a project and the AB model considers a user's behavior and heterogeneity. To illustrate the proposed approach, the proposed model was applied to a case study involving the construction of a bridge using certain assumptions and conducting an analysis under various scenarios. This case study demonstrates the significant importance of the proposed approach because it can incorporate both macro- and micro-elements that result in dynamic feasibility changes.

The integration of SD and ABM can provide a useful framework for analyzing the feasibility of a project. The framework offers a more valuable and flexible feasibility analysis than traditional feasibility analysis because it can enable feasibility simulation that incorporates individuals' behaviors and heterogeneity, overall system-level elements, the relationships among these elements, a sensitive analysis of individual- and system-level elements, and a test for future events. Consequently, a dynamic feasibility analysis enables project judges or policy makers to decide whether they should invest in a project or not taking into account the uncertainty of the environment and unexpected impacts.

However, some aspects of the approach can be improved. In particular, future research should develop a set of criteria or attributes of the modules/elements that are significant when a modeler integrates the SD model and the AB model. In this study, the interacting modules were described using a holistic perspective, and the interacting elements were specifically represented in the case study because the elements that relate to the integration of the SD model and the AB model differ depending on the project. Thus, a typological guideline on the integration of the SD model and the AB model would be useful. Also, the inclusion of other types of feasibility, instead of considering only economic feasibility, can allow the examination of feasibility from multiple perspectives.

Chapter 6

Conclusion

6.1 Summary and Contributions

As the complexity of recent technological knowledge continues to increase, there has been a growing demand for more systematic complexity management. To effectively manage the complexity of technological knowledge in terms of its emerging characteristics, this dissertation defined the three important dimensions of complexity as diversity, convergence, and dynamism. Then three managerial issues related to each aspect were addressed and resolved by utilizing and creatively combining appropriate methodologies through three research themes respectively (Table 6-1).

Overall, this dissertation can provide useful insights and appropriate methods for managing complexity of technological knowledge by addressing three different aspects, and by proposing creatively combined methods. Therefore, in practice, companies can effectively control the complexity of technological knowledge through management of three aspects of complexity. Specifically, companies can solve management problems arising from the three emerging characteristics of complexity by using suggested methods, and prepare for the future by formulating appropriate strategies. In addition, an effective technology policy can be established based on policy evaluation,

Table 6-1 Summary of this dissertation

	Complexity Dimension	Managerial Problem	Research Theme	Summary
Chapter 3. Managing Diversity in Complexity	Diversity	Difficulties in identifying current knowledge structure	Identification of intellectual structure of multidisciplinary fields	Using network centrality and brokerage measures to identify an overall view of intellectual structure of multidisciplinary field (nano)
Chapter 4. Managing Convergence in Complexity	Convergence	Difficulties in forecasting new technology trends	Prediction of technological convergence in emerging fields	Suggesting an approach wherein patent co-classification analysis and link prediction are used to predict technological convergence in emerging fields
Chapter 5. Managing Dynamism in Complexity	Dynamism	Difficulties in making a decision to invest in a project	Evaluation of feasibility of a project considering dynamic environments	Proposing a combined SD and ABM approach to analyze project feasibility in a dynamic environment

considering the complexity of technological knowledge by managing diversity, convergence, and dynamism. Also, each study has its unique contributions as listed in Table 6-2. The detailed summary and contributions of each chapter are described as follows.

Chapter 3. Managing Diversity in Complexity identified an overall view of intellectual structure of the multidisciplinary field based on the centrality and brokerage measures. Specifically, the knowledge source network and the technology element network were used to explore the intellectual structure of nanoscience and nanotechnology (nano), where multidisciplinary research is actively done. As a result, a microscopic and macroscopic view of the multidisciplinary structure of technological knowledge were obtained by identifying the important technology element regarding knowledge flow, and the intermediary role of each knowledge source regarding knowledge exchange. This study contributes to the field of studying intellectual structure of nano by identifying specific role of each knowledge source in terms of intermediate relationships in knowledge flow. In addition, it can help researchers find proper knowledge sources for acquiring specialized knowledge and searching new research opportunities.

Chapter 4. Managing Convergence in Complexity suggested an approach wherein patent co-classification analysis and link prediction are used to predict technological convergence in emerging fields. The proposed approach was applied to 3D printing technology to illustrate how the proposed approach can provide useful information of technological convergence. As a result, potential technology fields related to technological convergence were found. Besides, real instances for each potential convergence were investigated to validate the results. This study contributes to providing a useful framework for finding potential technological convergence in the future without assumption of past convergence. Therefore, the proposed approach can be utilized in various technologies and industries in the future. Furthermore, it can assist companies to establish future strategies by searching candidates for future technological convergence from various industries.

Chapter 5. Managing Dynamism in Complexity proposed a combined SD and ABM approach to analyze the feasibility of a technology-intensive and large-scale project in a dynamic environment. Here, the former SD part was used to elucidate the relationships among system elements that constitute project's benefits and costs, while the latter ABM part was used to depict users' emergent behavior with their heterogeneity. A case study of technology-intensive and large-scale project was conducted to provide an illustration of the proposed approach. This study contributes to offering a flexible feasibility analysis by enabling feasibility simulation that incorporates a sensitive analysis of individual- and system-level elements and a test for future events. Moreover, it enables project judges or policy makers to decide whether they should invest in a project or not considering the uncertainty of the environment and unexpected impacts.

Table 6-2 Contribution of this dissertation

	Implication
Overall Dissertation	• Providing useful insights and appropriate methods for managing complexity of technological knowledge by addressing three different aspects, and by proposing creatively combined methods • Enabling companies to effectively control the complexity of technological knowledge through management of three aspects of complexity • Assisting companies to solve management problems arising from the three emerging characteristics of complexity by using suggested methods, and to prepare for the future by formulating appropriate strategies • Helping to establish an effective technology policy based on policy evaluation, considering the complexity of technological knowledge by managing diversity, convergence, and dynamism
Chapter 3. Managing Diversity in Complexity	• Contributing to the field of studying intellectual structure of nano by identifying specific role of each journal in terms of intermediate relationships in knowledge flow • Helping researchers find proper journals for acquiring knowledge and new research opportunities
Chapter 4. Managing Convergence in Complexity	• Contributing to providing a useful framework for finding potential technological convergence in the future without assumption of past convergence (links) • Assisting companies to search candidates for future technological convergence from various industries and establish future strategies
Chapter 5. Managing Dynamism in Complexity	• Contributing to offering a flexible feasibility analysis by enabling feasibility simulation that incorporates a sensitive analysis of individual- and system-level elements and a test for future events • Enabling project judges or policy makers to decide whether they should invest in a project or not taking into account the uncertainty of the environment and unexpected impacts

6.2 Limitations and Future Research

Despite the contributions, this dissertation should be improved by addressing the limitations in future research. The limitations of each study that have been presented in the sub-conclusion of each chapter can be a good starting point of future research. In addition, the overall dissertation has a threefold limitation.

First and foremost, the managerial problems addressed in this research are quite limited in scope. Although this dissertation focuses on major managerial issues resulting from each aspect of complexity, there's still room for improvement. Other important research themes derived from three aspects of complexity can be incorporated in future research. For instance, other issues related to diversity, convergence, and dynamism, or new issues related to two or three aspects at the same time will be examined in future research.

Second, a more elaborate framework for complexity management of technological knowledge should be devised in future research. Although this dissertation presents the useful framework that covers three important aspects of complexity, this framework can be extended by analyzing more aspects of complexity. The inclusion of other aspects can provide richer understanding about the management of complexity. The elaborate framework for complexity management considering other aspects of complexity can be developed based on the prior studies about the dimension of complexity and complexity management.

Third, the comparison between the aspects of complexity is not allowed. In this dissertation, the case that is the most suitable for each study has been selected and analyzed. Consequently, different cases were used in each study to provide a clear illustration; however, they hinder a comparative analysis. If the case for each study is unified by the same technology in future research, then a comparison between the characteristics would be possible since the effect of technology type can be ignored. Furthermore, such attempt will enhance the understanding of technological knowledge by providing novel insights regarding the characteristics of complexity from a range of viewpoints.

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Appendix

Appendix A Supplementary Information about SD and ABM

Appendix A.1 System Dynamics (SD)

System dynamics (SD) is an approach used to understand the dynamic behavior of complex systems over time. The central concept is that all the objects in a system interact through causal relationships. What makes SD different from other approaches to studying complex systems is the use of stocks and flows, and feedback loops. First, SD focuses on dynamic complexity instead of detailed complexity (Sterman, 2000). With detailed complexity there is a large set of potential solutions, while with dynamic complexity, the area of interest is the changes that occur during different time periods. These changes are analyzed with the help of stock-and-flow diagrams. Stocks represent different kinds of accumulation (for instance, the amount of goods in a warehouse), while flows move the elements between the stocks. Second, SD modeling is mainly about discovering and representing feedback processes (Hjorth and Bagheri, 2006; Sterman, 2000). It determines the dynamics of a system along with the stock and flow structures, time delays, and nonlinearities. As a result, the interaction among variables is described as a causal loop diagram (CLD), which is a simple map of a system with all its constituent components and their interactions.

Running "what if" simulations to test certain strategies or policies on such a model can greatly aid in understanding how a system changes over time. Thus, a SD model usually consists of system-level state variables that generally represent aggregated information (Heath et al., 2011; Vincenot et al., 2011). The state variables in a SD model usually cannot represent individual entities. Furthermore, they are not suitable for simulating components that have an individual heterogeneity. Consequently, a high level of aggregation in a SD model can cause a loss of precision (Vincenot et al., 2011).

Appendix A.2 Agent-based Modeling (ABM)

Agent-based modeling (ABM) approach is used to simulate agents' autonomous behaviors and interactions with other agents, and their effects on an overall system. It is characterized as a bottom-up approach because the internal behaviors and interactions at micro level create the overall structure of a macro system (Grimm, 1999). The key instrument of the methodology is the "agent," an object that has the ability to make its own decision in a certain environment, behaves by a given decision rule, and interacts with other agents or the environment. In ABM, the model consists of interacting individuals/agents that differ from each other. Hence, the model is suitable for interacting components that have a high level of heterogeneity rather for an entire system (Macal and North, 2010; Vincenot et al., 2011).

Because of these characteristics, ABM is used to simulate human systems that consist of individual human behaviors. Examples of emergent phenomena abound in the social, political, and economic sciences; thus, the applications of ABM span a wide range of areas such as modeling agent behavior in the housing market (Ettema, 2011), developing the dynamic job shop scheduling system (Rajabinasab and Mansour, 2011), and modeling the diffusion of innovations (Kiesling et al., 2012).

Appendix B Prior Research on Formulating Integrated SD Model and AB Model

Type of integration		Topic (Reference)
Independent model		Cellular receptor dynamics (Wakeland et al., 2004)
		Investigating immune system aging (Figueredo and Aickelin, 2010)
Sequential model		Price adjustment process (Kim and Juhn, 1997)
		Emergent supply networks (Akkermans, 2001)
		Fishery management (BenDor et al., 2009)
Interacting model	Agents interacting with one SD model	Organizational project management (Hines and House, 2001)
		Design of financial stability (Martinez-Moyano et al., 2007)
		Product strategy decisions in automotive industry (Kieckhäfer et al., 2009)
	SD submodels embedded in agents	Supply chain management (Größler et al., 2003)
		Supply chain management (Schieritz and Größler, 2003)

Appendix C List of 73 Nano Journals

No.	Full Journal Title	Abbreviated Journal Title
1	ACM Journal on Emerging Technologies in Computing Systems	ACM J EMERG TECH COM
2	ACS Applied Materials and Interfaces	ACS APPL MATER INTER
3	ACS Nano	ACS NANO
4	Advanced Functional Materials	ADV FUNCT MATER
5	Advanced Materials	ADV MATER
6	AIP Advances	AIP ADV
7	Beilstein Journal of Nanotechnology	BEILSTEIN J NANOTECH
8	Biomedical Microdevices	BIOMED MICRODEVICES
9	Biomicrofluidics	BIOMICROFLUIDICS
10	Biosensors and Bioelectronics	BIOSENS BIOELECTRON
11	Current Nanoscience	CURR NANOSCI
12	Digest Journal of Nanomaterials and Biostructures	DIG J NANOMATER BIOS
13	Fullerenes Nanotubes and Carbon Nanostructures	FULLER NANOTUB CAR N
14	IEEE Transactions on Nanobioscience	IEEE T NANOBIOSCI
15	IEEE Transactions on Nanotechnology	IEEE T NANOTECHNOL
16	IET Nanobiotechnology	IET NANOBIOTECHNOL
17	International Journal of Nanomedicine	INT J NANOMED
18	International Journal of Nanotechnology	INT J NANOTECHNOL
19	Journal of Biomedical Nanotechnology	J BIOMED NANOTECHNOL
20	Journal of Computational and Theoretical Nanoscience	J COMPUT THEOR NANOS
21	Journal of Experimental Nanoscience	J EXP NANOSCI
22	Journal of Laser Micro Nanoengineering	J LASER MICRO NANOEN
23	Journal of Micro-Nanolithography MEMS and MOEMS	J MICRO-NANOLITH MEM
24	Journal of Micromechanics and	J MICROMECH

	Microengineering	MICROENG
25	Journal of Nano Research	J NANO RES-SW
26	Journal of Nanobiotechnology	J NANOBIOTECHNOL
27	Journal of Nanoelectronics and Optoelectronics	J NANOELECTRON OPTOE
28	Journal of Nanomaterials	J NANOMATER
29	Journal of Nanoparticle Research	J NANOPART RES
30	Journal of Nanophotonics	J NANOPHOTONICS
31	Journal of Nanoscience and Nanotechnology	J NANOSCI NANOTECHNO
32	Journal of Physical Chemistry C	J PHYS CHEM C
33	Journal of Physical Chemistry Letters	J PHYS CHEM LETT
34	Journal of Vacuum Science and Technology B	J VAC SCI TECHNOL B
35	Lab on A Chip	LAB CHIP
36	Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing	MAT SCI ENG A-STRUCT
37	Materials Express	MATER EXPRESS
38	Micro and Nano Letters	MICRO NANO LETT
39	Microelectronic Engineering	MICROELECTRON ENG
40	Microelectronics Journal	MICROELECTRON J
41	Microelectronics Reliability	MICROELECTRON RELIAB
42	Microfluidics and Nanofluidics	MICROFLUID NANOFLUID
43	Micromachines	MICROMACHINES-BASEL
44	Microporous and Mesoporous Materials	MICROPOR MESOPOR MAT
45	Microsystem Technologies-Micro-and Nanosystems-Information Storage and Processing Systems	MICROSYST TECHNOL
46	Nano	NANO
47	Nano Energy	NANO ENERGY
48	Nano Letters	NANO LETT
49	Nano Research	NANO RES

50	Nano Today	NANO TODAY
51	Nano-Micro Letters	NANO-MICRO LETT
52	Nanomaterials and Nanotechnology	NANOMATER NANOTECHNO
53	Nanomedicine-Nanotechnology Biology and Medicine	NANOMED-NANOTECHNOL
54	Nanomedicine	NANOMEDICINE-UK
55	Nanoscale and Microscale Thermophysical Engineering	NANOSC MICROSC THERM
56	Nanoscale	NANOSCALE
57	Nanoscale Research Letters	NANOSCALE RES LETT
58	Nanoscience and Nanotechnology Letters	NANOSCI NANOTECH LET
59	Nanotechnology	NANOTECHNOLOGY
60	Nanotoxicology	NANOTOXICOLOGY
61	Nature Nanotechnology	NAT NANOTECHNOL
62	Particle and Particle Systems Characterization	PART PART SYST CHAR
63	Photonics and Nanostructures-Fundamentals and Applications	PHOTONIC NANOSTRUCT
64	Physica E-Low-Dimensional Systems and Nanostructures	PHYSICA E
65	Plasmonics	PLASMONICS
66	Precision Engineering-Journal of The International Societies for Precision Engineering and Nanotechnology	PRECIS ENG
67	Recent Patents on Nanotechnology	RECENT PAT NANOTECH
68	Reviews on Advanced Materials Science	REV ADV MATER SCI
69	Science of Advanced Materials	SCI ADV MATER
70	Scripta Materialia	SCRIPTA MATER
71	Small	SMALL
72	Synthesis and Reactivity in Inorganic Metal-Organic and Nano-Metal Chemistry	SYNTH REACT INORG M
73	Wiley Interdisciplinary Reviews-Nanomedicine and Nanobiotechnology	WIRES NANOMED NANOBI

Appendix D Centrality Score of Nano Knowledge Sources

Technology element	Knowledge source (journal)	Out-degree	In-degree	Out-closeness	In-closeness	Betweenness
Mt	ACS APPL MATER INTER	0.275	0.100	0.263	0.412	0.621
G	ACS NANO	0.250	0.500	0.261	0.526	5.799
Mt	ADV FUNCT MATER	0.175	0.300	0.245	0.476	0.094
Mt	ADV MATER	0.275	0.575	0.270	0.588	16.841
G	AIP ADV	0.050	0.000	0.241	0.143	0.000
B	BIOMED MICRODEVICES	0.025	0.025	0.216	0.308	0.000
B	BIOMICROFLUIDICS	0.025	0.025	0.216	0.308	0.000
E	BIOSENS BIOELECTRON	0.175	0.075	0.250	0.348	0.855
G	IEEE T NANOTECHNOL	0.050	0.000	0.235	0.143	0.000
B	INT J NANOMED	0.025	0.000	0.233	0.143	0.000
B	J BIOMED NANOTECHNOL	0.025	0.025	0.229	0.247	0.000
G	J COMPUT THEOR NANOS	0.025	0.000	0.221	0.143	0.000
E	J MICROMECH MICROENG	0.025	0.050	0.216	0.313	1.603
Mt	J NANOMATER	0.125	0.000	0.250	0.143	0.000

Mt	J NANOPART RES	0.225	0.000	0.268	0.143	0.000
G	J NANOSCI NANOTECHNO	0.300	0.050	0.265	0.320	8.558
I	J PHYS CHEM C	0.275	0.525	0.263	0.533	8.534
G	J PHYS CHEM LETT	0.150	0.150	0.241	0.440	0.000
E	J VAC SCI TECHNOL B	0.075	0.050	0.231	0.345	2.372
G	LAB CHIP	0.175	0.175	0.248	0.430	16.416
I	MAT SCI ENG A-STRUCT	0.025	0.025	0.146	0.146	0.000
E	MICROELECTRON ENG	0.100	0.025	0.241	0.261	0.093
I	MICROFLUID NANOFLUID	0.025	0.025	0.216	0.308	0.000
I	MICROPOR MESOPOR MAT	0.050	0.050	0.235	0.364	0.000
E	MICROSYST TECHNOL	0.025	0.000	0.196	0.143	0.000
I	NANO ENERGY	0.100	0.000	0.245	0.143	0.000
G	NANO LETT	0.200	0.725	0.247	0.645	8.391
G	NANO RES	0.075	0.025	0.237	0.313	0.000
G	NANO TODAY	0.075	0.025	0.237	0.313	0.000
B	NANOMEDICINE-UK	0.050	0.000	0.234	0.143	0.000
G	NANOSCALE	0.350	0.175	0.274	0.435	14.990
G	NANOSCALE RES LETT	0.125	0.000	0.250	0.143	0.000

G	NANOSCI NANOTECH LET	0.025	0.025	0.230	0.250	0.000
G	NANOTECHNOLOGY	0.225	0.400	0.261	0.500	8.056
G	NAT NANOTECHNOL	0.025	0.300	0.215	0.476	0.000
G	PART PART SYST CHAR	0.100	0.000	0.245	0.143	0.000
I	PHYSICA E	0.075	0.000	0.240	0.143	0.000
E	PLASMONICS	0.050	0.000	0.235	0.143	0.000
Mt	SCI ADV MATER	0.075	0.025	0.240	0.250	0.000
Mt	SCRIPTA MATER	0.025	0.025	0.146	0.146	0.000
G	SMALL	0.225	0.275	0.267	0.471	3.574

Appendix E Brokerage Score of Nano Knowledge Sources in Weighted Version

Technology element	Knowledge source (journal)	Coordinator	Gatekeeper	Representative	Consultant	Liaison	Total
Mt	ACS APPL MATER INTER	0.0	0.0	0.3	0.0	1.0	1.3
G	ACS NANO	7.7	12.7	5.0	1.1	7.4	33.9
Mt	ADV FUNCT MATER	0.0	0.0	0.0	0.4	0.3	0.7
Mt	ADV MATER	2.0	10.4	7.1	22.7	13.0	55.0
G	AIP ADV	0.0	0.0	0.0	0.0	0.0	0.0
B	BIOMED MICRODEVICES	0.0	0.0	0.0	0.0	0.0	0.0
B	BIOMICROFLUIDICS	0.0	0.0	0.0	0.0	0.0	0.0
E	BIOSENS BIOELECTRON	0.0	0.0	0.0	1.0	1.0	2.0
G	IEEE T NANOTECHNOL	0.0	0.0	0.0	0.0	0.0	0.0
B	INT J NANOMED	0.0	0.0	0.0	0.0	0.0	0.0
B	J BIOMED NANOTECHNOL	0.0	0.0	0.0	0.0	0.0	0.0
G	J COMPUT THEOR NANOS	0.0	0.0	0.0	0.0	0.0	0.0
E	J MICROMECH MICROENG	0.0	0.0	1.0	0.0	0.0	1.0
Mt	J NANOMATER	0.0	0.0	0.0	0.0	0.0	0.0

Mt	J NANOPART RES	0.0	0.0	0.0	0.0	0.0	0.0
G	J NANOSCI NANOTECHNO	1.0	6.0	2.5	0.0	5.0	14.5
I	J PHYS CHEM C	2.0	16.5	10.1	13.0	16.0	57.5
G	J PHYS CHEM LETT	0.0	0.0	0.0	0.0	0.0	0.0
E	J VAC SCI TECHNOL B	0.0	1.0	0.0	0.0	0.0	1.0
G	LAB CHIP	0.0	4.0	4.5	4.0	24.3	36.8
I	MAT SCI ENG A-STRUCT	0.0	0.0	0.0	0.0	0.0	0.0
E	MICROELECTRON ENG	0.0	0.0	0.3	0.0	0.0	0.3
I	MICROFLUID NANOFLUID	0.0	0.0	0.0	0.0	0.0	0.0
I	MICROPOR MESOPOR MAT	0.0	0.0	0.0	0.0	0.0	0.0
E	MICROSYST TECHNOL	0.0	0.0	0.0	0.0	0.0	0.0
I	NANO ENERGY	0.0	0.0	0.0	0.0	0.0	0.0
G	NANO LETT	21.5	14.3	11.0	0.5	5.4	52.8
G	NANO RES	0.0	0.0	0.0	0.0	0.0	0.0
G	NANO TODAY	0.0	0.0	0.0	0.0	0.0	0.0
B	NANOMEDICINE-UK	0.0	0.0	0.0	0.0	0.0	0.0
G	NANOSCALE	9.4	12.2	2.5	0.3	1.8	26.2
G	NANOSCALE RES LETT	0.0	0.0	0.0	0.0	0.0	0.0

G	NANOSCI NANOTECH LET	0.0	0.0	0.0	0.0	0.0	0.0
G	NANOTECHNOLOGY	3.6	6.4	8.7	0.2	9.7	28.5
G	NAT NANOTECHNOL	0.0	0.0	0.0	0.0	0.0	0.0
G	PART PART SYST CHAR	0.0	0.0	0.0	0.0	0.0	0.0
I	PHYSICA E	0.0	0.0	0.0	0.0	0.0	0.0
E	PLASMONICS	0.0	0.0	0.0	0.0	0.0	0.0
Mt	SCI ADV MATER	0.0	0.0	0.0	0.0	0.0	0.0
Mt	SCRIPTA MATER	0.0	0.0	0.0	0.0	0.0	0.0
G	SMALL	2.7	2.6	0.0	0.0	0.0	5.3

Appendix F Description and Assumption of Overall Variables in Combined Model

Name of variable	Units	Definition/Equation	Data/Assumption
Potential user	n/a	Driver in the outside regions of the bridges	10,000
Zone user	n/a	Driver in the surrounding regions of the bridges	-
Area user	n/a	Driver in the entrance regions of the bridges	-
Zone user rate	%	Rate of flow from potential users to zone users	50 in a basic scenario
Area user rate	%	Rate of flow from zone users to area users	20 in a basic scenario
Existing road user	n/a	Driver who is using an existing road at the moment	-
New road user	n/a	Driver who is using a new road at the moment	-
Affordable velocity	km/hr	Marginal range of velocity a driver will tolerate	uniform(50,70)
New road selection probability	%	Probability of selecting a new road, which represents a degree of progressive tendency	uniform(0,1)
Total traffic	n/a	Approximate number of total traffic per hour	-
Ideal velocity 1	km/hr	Ideal velocity of an existing road	60
Ideal velocity 2	km/hr	Ideal velocity of a new road	80
Capacity of road 1	n/a	Capacity of an existing road per hour	400
Capacity of road 2	n/a	Capacity of a new road per hour	625

Road length 1	km	Length of an existing road	100
Road length2	km	Length of a new road	80
Velocity of road 1	km/hr	Actual velocity of an existing road: Velocity of road 1 = Ideal velocity 1* (Capacity of road 1 / (Capacity of road 1 + Traffic of road 1))	-
Velocity of road 2	km/hr	Actual velocity of a new road: Velocity of road 2 = Ideal velocity 2* (Capacity of road 2 / (Capacity of road 2 + Traffic of road 2))	-
Velocity of road 0	km/hr	Actual velocity of an existing road before construction: Velocity of road 0 = Ideal velocity 1* (Capacity of road 1 / (Capacity of road 1 + Traffic of road 0))	-
Vehicle operating cost (OC) per km according to velocity lookup table	n/a	Lookup Table of vehicle operating cost per km classified by velocity	Velocity (km/hr) / Cost (₩/km): 10 / 332.99 20 / 267.75 30 / 232.72 40 / 202.16 50 / 183.63 60 / 174.48 70 / 168.82 80 / 161.19 90 / 159.28 100 / 160.12 110 / 162.53 120 / 167.36

Vehicle OC per km of road 1	₩/km	Cost of operating a vehicle per km at a certain velocity on an existing road: Vehicle OC per km of road 1 = Vehicle OC per km according to velocity lookup table (Velocity of road 1)	-
Vehicle OC per km of road 2	₩/km	Cost of operating a vehicle per km at a certain velocity on a new road: Vehicle OC per km of road 2 = Vehicle OC per km according to velocity lookup table (Velocity of road 2)	-
Vehicle OC per km of road 0	₩/km	Cost of operating a vehicle per km at a certain velocity on an existing road before construction: Vehicle OC per km of road 0 = Vehicle OC per km according to velocity lookup table (Velocity of road 0)	-
Total vehicle OC	₩	Total cost of operating a vehicle: Total vehicle OC = Vehicle OC per km of road 1*Road length 1 + Vehicle OC per km of road 2* Road length 2	-
Traffic of road 1	n/a	Number of drivers using an existing road after construction, which changes over time	-
Traffic of road 2	n/a	Number of drivers using a new road after construction, which changes over time	-
Traffic of road 0	n/a	Number of drivers using an existing road before construction, which changes over time	-
Road using time	hr	Time spent on the road: Road using time = Road length/Velocity of road	-

Time value	₩/hr	Time value per car	14,990
Total travel time cost	₩	Total cost of travel time: Total travel time cost = Road using time*Time value*Total traffic	-
Total accident cost	₩	Total cost of car accident: Total accident cost = (Number of traffic accidents/deaths per road length per car*Accidents/deaths cost + Number of property damage per road length per car *Property damage cost)*Road length*Total traffic	-
Air pollution cost per km according to velocity lookup table	n/a	Lookup Table of air pollution cost per km classified by velocity	Velocity (km/hr) / Cost (₩/km): 10 / 67.57 20 / 34.38 30 / 23.68 40 / 18.32 50 / 15.11 60 / 12.96 70 / 11.39 80 / 10.21 90 / 9.29 100 / 8.54
Total air pollution cost	₩	Total cost of air pollution: Total air pollution cost = Air pollution cost per km according to velocity lookup table (Velocity of road) *Road length*Total traffic	-
Enter decision zone	n/a	Entering a zone where a driver should make a decision on selecting a road (Triggered by “rate” = 0.5/hour)	-

Selected road	n/a	Variable used when making a decision on selecting a road (i.e. initial value is null and "1" means a driver decides to use an existing road)	-
Too much traffic on the new road	n/a	Compare velocity of a new road with the expected level: Velocity of road2 < affordable velocity	-
Conservative	n/a	Compare probability of selecting a new road with the assumed level: New road selection probability < 0.3	-
Too much traffic on the existing road	n/a	Compare velocity of an existing road with velocity of a new road: Velocity of road1 < Velocity of road 2	-
Radical	n/a	Compare probability of selecting a new road with the assumed level: New road selection probability > 0.7	-
Selected road = null	n/a	Code to initialize the value of "Selected road" to null (Code: Selected road = null;)	-
Select an existing road	n/a	Code to set "Selected road" to "1" (Code: Selected road = "1";)	-
Select a new road	n/a	Code to set "Selected road " to "2" (Code: Selected road = "2";)	-
Go to road 1	n/a	Decision to go to existing road (Condition: Selected road = "1")	-
Go to road 2	n/a	Decision to go to new road	-

		(Condition: Selected road = "2")	
Move out 1	n/a	Moving out of an existing road after spending some time (Triggered by "timeout" = uniform(1,2)*hour)	-
Move out 2	n/a	Moving out of a new road after spending some time (Triggered by "timeout" = uniform(1,2)*hour)	-
Construction cost	₩	Construction cost	4,000,000,000
Incidental cost	₩	Incidental cost	200,000,000
Compensation cost	₩	Compensation cost	100,000,000
Extra cost	₩	Extra cost	200,000,000
Maintenance cost	₩/day	Maintenance cost	255,000
Population impact	n/a	An increase in the number of users that results from the natural population growth	Area and zone user rate increases 1% annually
Policy impact	n/a	An increase in the number of users that results from a policy impact	Area and zone user rate increases 10% after three years
Feedback impact	n/a	An increase in the number of users that results from a vitalization of the local economy	Area user rate increases in proportion to the number of new road users

초 록

지속적인 기술혁신을 창출하기 위해서 연구개발에 관련된 데이터와 정보를 가공하여 이를 창의적인 지식으로 전환시키는 기술지식경영이 강조되고 있다. 특히 최근 기술지식의 복잡성이 지속적으로 증가함에 따라 복잡성을 고려한 보다 체계적인 기술지식경영에 대한 요구가 증가하고 있다. 기술지식은 더 이상 하나의 단일 기술이 아닌 다양한 관련 기술과 학제를 포함하게 되었으며, 다양한 기술들이 서로 융합하여 새로운 기술로 발전하는 양상을 나타내고 있다. 또한, 기술지식을 활용하는 사람들이 더욱 다양해지고 그 파급효과가 광범위해짐에 따라 기술지식은 더욱 동적인 환경에 노출되고 있다.

이에, 본 학위 논문은 기술지식의 복잡성을 구성하는 특성에 대한 연구를 수행하며, 특히 복잡성으로 인해 발생하는 주요 경영 문제를 해결한다. 구체적으로, 본 학위 논문은 최근 기술지식의 복잡성을 구성하는 특성을 다양성, 융합성, 동태성로 정의하고 각 특성에 관련된 세 가지 연구 문제를 다룬다. 다양화된 기술지식의 구조 탐색 문제, 기술융합이 활발한 상황에서 기술 트렌드 예측 문제, 동적인 환경에 놓인 대형 기술 프로젝트 평가 문제를 다룬 세 가지 세부 연구는 적합한 방법론을 활용 및 창조적으로 결합하여 각 문제들을 효과적으로 다룬다.

첫 번째 연구는 기술지식의 다양성 관리 측면에서 기술지식의 구조 분석을 다룬다. 최근 기술지식은 다학제적인 성격을 가지며, 연구개발 전략의 올바른 방향을 설정하기 위해서 그 구조를 파악하고 연구 동향을 이해하는 것이 중요하다. 본 연구에서는

다학제적인 기술지식의 구조를 파악하는 방법으로 저널 인용 네트워크와 네트워크 분석을 활용한 프레임워크를 제시한다. 구체적으로, 저널 인용 네트워크를 구축하고 네트워크 중심성(centrality) 측정 및 중개(brokerage) 분석을 활용하여 다학제 연구가 대표적으로 활발히 일어나고 있는 나노과학기술 분야의 지적 구조를 탐색한다. 제안된 접근은 지식의 흐름 측면에서 중요한 기술 요소(technology element)와 지식 교환 측면에서 지식 원천(knowledge source)의 중개 역할을 파악함으로써 기술지식의 다학제적인 구조에 대한 미시적, 거시적 관점을 제공할 수 있다는 점에서 의의가 있다.

두 번째 연구는 기술지식의 융합성 관리 측면에서 기술융합의 예측을 다룬다. 오늘날 기술지식은 빠르게 진화하고 있으며, 융합을 통해 새로운 기술이 창출되는 양상을 보이고 있다. 이에 따라, 기술 간의 경계가 흐려지고 있으며 새로운 기술 트렌드를 예측하는 것이 더욱 어려워지고 있다. 본 연구에서는 새롭게 등장하는 유망 기술의 기술융합을 예측하는 방법으로 특허동시분류분석과 링크예측기법을 활용한 프레임워크를 제시한다. 제안된 접근은 네트워크의 특성을 바탕으로 잠재적인 링크를 예측하므로 과거에 존재 않았더라도 미래에 나타날 가능성이 높은 기술융합을 파악할 수 있다는 장점을 가진다. 이해를 돕기 위해, 제안된 접근은 3D 프린팅 기술에 적용되었으며, 향후 다양한 기술 및 산업에서 활용될 수 있을 것으로 기대된다.

마지막으로, 세 번째 연구는 기술지식의 동태성 관리 측면에서 대형 기술 프로젝트의 평가를 다룬다. 기술지식을 활용하는 사람들이 다양해지고, 기술지식이 영향을 미치는 파급효과의 범위가

확대됨에 따라 기술 투자 프로젝트의 의사결정 문제가 더욱 중요해지고 있다. 본 연구에서는 동적인 환경에서 프로젝트의 타당성을 분석하는 방법으로 시스템 다이내믹스(system dynamics)와 행위자 기반 모델링(agent-based modeling)을 결합한 프레임워크를 제시한다. 제안된 접근에서 시스템 다이내믹스 부분은 프로젝트의 비용과 효익을 구성하는 시스템 요소 간의 관계를 설명하고, 행위자 기반 모델링 부분은 사용자의 이질성(heterogeneity)을 고려한 창발적 행동(emergent behavior)을 묘사한다. 사례 연구를 통해 제안된 접근의 적용 가능성을 보였으며, 제안된 접근은 동적인 환경에서 프로젝트의 실현 가능성을 분석하기 위한 유연한 프레임워크를 제공할 수 있다는 점에서 의의가 있다.

주요어: 기술지식, 복잡성 관리, 다양성, 융합성, 동태성, 네트워크 분석, 링크예측, 시스템 다이내믹스, 행위자 기반 모델링

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