

Analysis of Knowledge Combination Process: From Engineering Science Perspective

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지식종합화과정의 분석: 엔지니어링 사이언스 관점

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Abstract We consider organizational knowledge combination process. Previous literature investigated the issue from either managerial or social aspects, emphasizing on a part of the whole process and limiting to qualitative analyses. Here we propose an integrative and quantitative approach which considers knowledge combination process from engineering perspective. We employ a queueing network model and techniques to capture the process of interactions of entities in the knowledge combination environment. By doing so, we are able to understand the performance of the knowledge combination process. The performance measures derived can provide valuable implications for managerial decisions such as planning and controlling the knowledge combination process.

요약 본 논문은 조직원의 지식을 종합화하는 프로세스를 고찰한다. 이전의 관련 연구는 관리적, 사회적 관점에서 프로세스의 부분에 국한하거나 정성적 분석에 초점을 맞추었다. 본 연구는 프로세스를 통합적이고 계량적으로 살펴보는 엔지니어링 접근법을 제안한다. 이를 위해서 대기네트워크 이론을 도입하여 지식종합화 환경의 구성요소들 간의 상호작용을 포착하는 모델과 적용 방법론을 기술한다. 이를 통해서 지식종합화 프로세스의 성과지표를 도출할 수 있고, 이러한 지표는 지식종합화 프로세스를 개선하기 위한 계획이나 통제에 효과적으로 사용이 될 수 있을 것이다.

Key Words : Knowledge combination process, Queueing network, Engineering, Social network analysis

1. Introduction

Organizational knowledge has been considered to be sources of sustainable competitiveness [1,2] forcing most of the companies to introduce their own knowledge management systems in their organizations. The key question of the knowledge management system is whether it contributes to generate relevant organizational knowledge when and where it is needed. However, knowledge creation process has been thought to be mystical and assumed to be structurally ill-defined. For this reason, the process is loosely understood and research

on this area is limited to managerial and social considerations.

Since organizational knowledge is created by a set of organizational members and supporting technologies, we need to examine complicated interactions among the members, which makes the analysis not trivial. Thus most research on this area resorts to conceptual propositions and statistical empirical models to study a part of the process, not as a holistic process.

Recently interdisciplinary research tends to recognize service process as science just like early 20th century when we started to look at manufacturing rigorously from

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engineering process. Likewise we view organizational knowledge creation as knowledge provision service. Once we consider it as science, we may apply existing body of engineering theories to manage knowledge creation process in systematic ways.

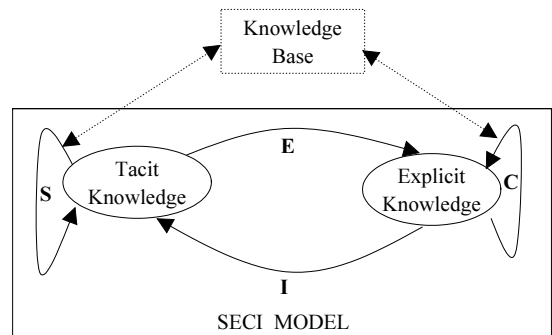
Previous literature investigated the issue from either managerial or social aspects, emphasizing on a part of the whole process and limiting to qualitative analyses. To remedy these shortcomings, social network analysis techniques are sometimes applied to figure out the informal knowledge sharing structure of relationship among organizational members. From this analysis, a set of structural measures such as centrality, structural holes, density, and so on. But it does not capture the knowledge creation process itself.

Instead, a queueing network model, which has been successfully used in diverse service fields, is suitable to accommodate the system of knowledge creating process fully and capture the interactions of system components. By doing so, we are able to understand the performance of the knowledge creating process. The performance measures derived can provide valuable implications for managerial decisions such as planning and controlling the knowledge creating process. This is the main objective of this paper to extend the current state of research on knowledge creation process by employing a rigorous engineering approach.

The structure of the paper is as follows: In section 2 we describe the knowledge creation process, knowledge combination process in particular, which we investigate in this paper from a network perspective. For the subsequent development of our argument, we present a general model for knowledge combination process in section 3. In section 4 we discuss why we need the science concept in knowledge combination process. We also point out the limitation of social network analysis as a quantitative analysis method for knowledge creating process per se. In section 5, a queueing network model, the method we propose in this paper, is delineated. In section 6 we discuss the implications of the model and the performance measure from the analysis of the model, followed by concluding remarks in section 7.

2. Knowledge creation process

Types of knowledge are generally dichotomized as tacit and explicit, depending on the extent to be able to codify. Since tacit knowledge is built upon long experience-based learning, it is hard to articulate and expensive to diffuse to other people. On the other hand, explicit knowledge can be easily stored and shared using information and communication technology (ICT). By deepening the meaning of each knowledge type and transforming into other types, organizations are able to apply knowledge resources much more readily for innovation and problem solving. Nonaka et al. [2] recognized the importance of knowledge creating capability and proposed an integrative model of knowledge creating process as in Figure 1.



[Fig. 1] Knowledge base integrated SECI Model
(Note: SECI model section in box is modified from Bolloju [4] and the other is added by the author.)

In the model, four processes such as socialization, externalization, combination, and internalization (SECI) are defined: By socialization process they meant that organizational members should utter their own implicit knowledge in the public so that the organization recognizes the tacit knowledge of others. For the tacit knowledge to be useful, the organization should try to turn it into explicit knowledge by externalization process. With socialization and externalization processes the value of knowledge becomes more organization-oriented and ready to applicable, respectively. Moreover the organizational explicit knowledge needs to be integrated with other explicit knowledge in the organization so that new explicit knowledge is created, which is called the combination process. In this type of knowledge conversion, individuals exchange and combine knowledge through such media as documents, meetings, telephone

conversations, or ICT [2]. Nonaka et al. noted that knowledge created by the combination process is most frequently occurred in the middle managers. Finally each of the individual members should internalize the organizational explicit knowledge to be assimilated in his own working environment and to make it as his own tacit knowledge.

To make knowledge creating process complete, repository of organizational knowledge base is added to the SECI model. The repository plays an important role in articulating tacit knowledge and creating new explicit knowledge. We deal with the repository and its interactions with knowledge workers in section 3.

Here we review literatures of related research on knowledge creation and management. Hansen et al [4] proposed a contingent approach that an organization should adopt knowledge management strategy of either personalization or codification, depending on the company's strategy of competition, source of profit creation, speed of growth, and the role of knowledge for the organization. Choi et al [5] tested the Hansen et al.'s strategy in the Nonaka's four stages of knowledge creating processes. They showed that personalization strategy is more effective for socialization and codification strategy is more effective for combination process. Research on the relationship between knowledge management and ICT, Choi et al. [6] studied the relationship among the factors affecting knowledge management systems usage, knowledge activities such as absorption, creation, sharing, diffusion and usage, and organization environmental factors. Lee et al [7] investigated the role of ICT for the effective management of the Nonaka's four stages model.

Unlike the above literature, Bohn [8] claimed that the usefulness of knowledge comes from the degree of explicitness of knowledge. Suppose we have the following relationship between independent variables and dependent variable, $Y = f(x_1, x_2, \dots, x_n)$. Here we have n pieces of knowledge affecting Y . Those pieces should not be interpreted either completely known or unknown. But they are in the continuum of explicitness. The usefulness level of the knowledge needs to be judged from the power of predictability and explainability of causality. He argued that once we can manipulate the independent variables or knowledge to control the dependent variable, the relational knowledge becomes a scientific knowledge.

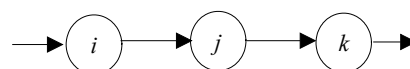
2.1 Knowledge combination process

In this paper we specifically deal with knowledge combination process. Let's consider an example to illustrate knowledge combination process. Brownian motion process model has been well established in Physics for long time. Suppose we want to adopt the model for stock market forecasting purpose. For the model to be effectively used in the new situation, someone who knows the model well should inform the details to the stock market analysts. Once they understand the model clearly, they need to modify the model so that it is suitable to stock market. The modification is done by experts in such areas as securities, futures, derivatives, and so on. That is, knowledge is added on by individual experts until they determine the modified model is good enough for stock market.

2.2 Archetypes of knowledge combination process

Pointing out the problems of static nature of existing organizational chart which describes the authority and responsibility among the entities of an organization, Minzberg et al. [9] proposed the organigraph concept to capture the real business process and interactions among the entities of an organization. They observed that the interactions can be categorized into four types such as set, chain, hub, and web as in Figure 2 through 4. The figures are modified from those in [9,10]. Since the type of business process determines the role of participating entities, we believe that the entities in a specific business process perform their roles in knowledge combination process. A set, a most primitive type among the four, works independently without interacting with other entity in the organization like a professor or lawyer. There is no significant knowledge combination activities involved in this case.

In a chain organization, the business process is performed in a liner way as in Figure 2.



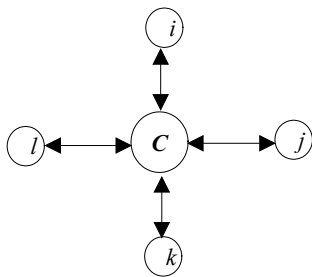
[Fig. 2] Chain process

In the figure i refers to entity i and the arrow indicates

the direction of business activity. In this type of organization the most important knowledge type is procedural. i and j are independent experts in each area and thus they are likely to participate in that order to combine procedural knowledge in that organization.

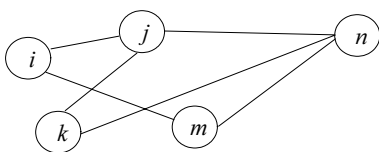
In a hub organization, the business process is coordinated by a center and satellite entities are controlled by the center [9], while they are not linked or loosely each other as in Figure 3.

Knol, an online encyclopedia run by Google, takes this approach to build up knowledge. Knowledge update is only allowed by the owner of knowledge, while other participants only can provide their suggestions. The knowledge owner determines whether the inputs are to be combined or not. This type of process is characterized by new product development and R&D activities. In that organization, knowledge is not combined by entities independently, but the center C may initiate the knowledge combination process to i to fulfill the organization's objectives, and then i responds to C by contributing his own expertise.



[Fig. 3] Hub process

Finally in a web type, there is no entity controlling the process, but the entities autonomously participates in the interactions. In the Figure 4, j has three possibilities to be connected to the others for soliciting knowledge. But depending on the type of knowledge, j may choose to activate a link to n instead of i or k .



[Fig. 4] Web type process

A representative case is wikipedia in which knowledge combination process is never ending. Community members of wikipedia have capacity to add or modify the knowledge with their discretion. In this type of organization, knowledge required is ad-hoc and not well structured. Due to these characteristics, request to other entities for knowledge combination activities may change from time to time. Thus, compared with chain and hub structures, the network structure denotes a set of complex interactions among the entities.

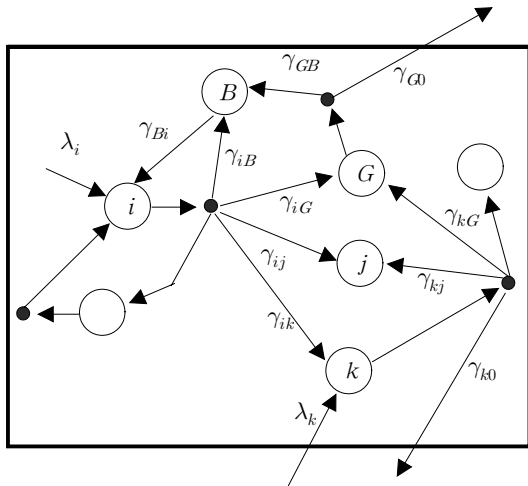
3. General model of knowledge combination process

Based on these three archetypes excluding the set type, we propose a general model of knowledge combination process which encompasses the three archetypes. In the system, we include ICT component, especially organizational knowledge repository from which entities can retrieve existing knowledge and in which newly created knowledge is stored. Also to make the system complete we include a knowledge base gatekeeper. For clear presentation purposes, let's define the components of the system. i , j , and k refer to entities participating in knowledge combination. Entities can be individuals, work units, or ICT systems. B , G , and θ denote knowledge base, knowledge base gatekeeper and outside the organization.

Figure 5 is the model we consider for knowledge combination process. Explanation of the model is as follows: First for initiation of knowledge combination, λ_i refers to the rate of knowledge composition request initiated by i . The rate can be measured in a specific duration such as a week or a month. The request may come from inside the organization as in i or from the outside as in k .

Second for the routing, once i finishes the processing on the initial knowledge using i 's domain expertise, the next step i can choose is 1) if the knowledge is completed, then it will be forwarded to G , the knowledge base gatekeeper, 2) if the knowledge is not completed yet, then to make the knowledge more complete, i may route the incomplete knowledge to knowledge base for querying

the existing organizational knowledge, 3) i may forward to either j or k for further knowledge combination, or 4) it may discard the knowledge when the knowledge on hand is determined useless as in j 's decision.



[Fig. 5] Model of knowledge combination process
(Note: Box denotes the boundary of an organization.)

Third, γ_{ij} refers to the propensity of routing from i to j . Thus the sum of the routing propensity from i to all other entities should be 1.

Fourth, all the entities need to spend processing time to do knowledge combination work. But at B , the processing time is negligible since most of the processing involves knowledge retrieval.

One more thing to be noted is that each entity may have to participate in many pieces of knowledge combination activities. That is, a queue is involved for each entity.

Once entity k determines that the knowledge combination is completed, it is forwarded to the knowledge base gatekeeper, G who in turn judges whether the knowledge is worthwhile to be stored in the knowledge base. If so, meta data for the knowledge is created and knowledge itself is kept there. Otherwise, it is discarded. Thus, in the model, we assume that all the knowledge combination work completed by entities is sent to G .

We note that the three archetypes presented can be derived from Figure 5, by controlling knowledge combination initiator and routing propensity. For example,

in Figure 2, most often the team leader, i initiates knowledge combination, that is $\lambda_j = 0$ ($j \neq i$) and $\gamma_{ij} = 1$.

4. Why should knowledge combination process be a science?

As described in Figure 5, the interaction of entities in an organization to combine knowledge is complex. To understand the system functionality, we need to examine parameters and their interactions: λ_i , γ_{ij} , processing rate of μ_i for each i . As Bohn [8] pointed out, once we know the effects of parameters and the resulting system performance, organizational knowledge combination process can be effectively controlled. Consequently from the model we need to understand such measures as the number of completed knowledge combination works at the organizational level and the average number of knowledge works in process for each entity. From these measures managers can reconsider the organization structure, staffing, ICT investment, education and training, incentives and so on.

We also recognize the knowledge combination as knowledge service operation provided by entities to the organization which is a consumer of knowledge.

For the effective and efficient knowledge service, we need to analyze the system in more rigorous way. Recently service science is attracting much research attention since there exist ample opportunities to improve the quality and the level of service [11,12]. For example, IBM, a forerunner of service science research, coined a term SSME (Service Science, Management, and Engineering) "to describe Services Sciences, an interdisciplinary approach to the study, design, and implementation of services systems - complex systems in which specific arrangements of people and technologies take actions that provide value for others. More precisely, SSME has been defined as the application of science, management, and engineering disciplines to tasks that one organization beneficially performs for and with another" ("service science", on wikipedia.com.).

In knowledge management area, most research is done on managerial, technical and social issues, leaving

engineering aspects are completely left out. Can engineering not be applied to knowledge management at all? As is described in [13], let's consider an example which shows engineering science in a service area. In the early 20th century the Erlang system was introduced. The Erlang formula is to measure the performance of a telephone exchange with finite switch capacity. Before the introduction of the Erlang formula, managerial decisions on the capacity of the exchange and on the psychological and social effects due to the queue were made independently, not based on concrete system performance.

4.1 Engineering by social network analysis

Social network analysis is to study the structure of relationships among members of a group. Relationship can be represented with either binary or weighed measures. It captures the relational properties of individuals as well as the groups as a whole. The major indices of the analysis are centrality, centralization, clustering, distance, structural hole, closure, and so on [14,15].

Social network analysis has been applied to knowledge management. For example, using a social network in informal organizational settings, Cross and Prusak [16] showed how different roles such as central connectors, boundary spanners, information brokers, and peripherals can be figured out. A central connector is a central person who takes many links from other persons for work-related advice. The person contributes to the organization positively for improving productivity, but he may be a bottleneck. A boundary spanner serves to connect a local network to remote networks, so that the local network is attached to outside networks. In an R&D organization, the role of the boundary spanner is crucial to obtain knowledge not available inside. An information broker connects several local networks so that the whole network work together cohesively. Finally a peripheral is not much connected to others, but the person possess his own domain expertise.

On the other hand, Krackhardt et al. [17] categorized social networks into three types such as information, trust, and communication. Among the three, information network is utilized when an individual needs to find knowledge for problem solving.

The importance and implications of social network

analysis in knowledge creation was empirically validated in [18].

In sum, the research employing a social network analysis technique is limited to the study of the relational structure latent in organization and to investigation of how to promote the social network for organizational performance in humanistic ways. Therefore the current applications of social network analysis is not appropriate to deal with the knowledge combination process as in Figure 5.

5. Knowledge combination process as a process of network of queues

We again consider the model in Figure 5. We map the model into a network of queues. For the mapping, the parameters such as processing request rate λ_i , processing rate μ_i , and routing propensity γ_{ij} need to be figured out. The parameters can be obtained from hard sources such as system log data and project management reports and soft sources such as surveys and interviews. Since an organization gradually adopts performance measuring system such Balanced Scorecard [19], we expect the related data can be obtained more easily and accurately. Note that compared with the parameters used in social network analysis, γ_{ij} , for all i and j , has similar meaning, but all other parameters in Figure 5 cannot be accommodated in social network analysis. It implies that the model encompasses much more information and complexity than that of social network analysis. Since the purpose of this paper is to show how to apply engineering science to the analysis of knowledge combination process, we do not go into detail for data collections.

Assuming we have the set of parameters, we can analyze the model or the network of queues by simulation or analytically. Here we provide analytical solutions by simplifying the problem so that readers can see the implications of the model. As in the Erlang queueing system, we assume that processing request and time spent for combination process at i follows the Poisson distribution with mean λ_i and Exponential distribution with $1/\mu_i$ and a single entity works for the processing. Then the model can be seen as N M/M/1 queues where

N is the number of entities in the model. We assume that the processing times are independent of the processing request process. This type is called Jackson network [20]. For notational simplicity, the corresponding vectors and matrices from the parameters are written without subscripts. So γ is $N \times N$ matrix, and λ and μ are $1 \times N$ vectors. If γ is ergodic, there exists a unique solution of vector π such that $\pi = \lambda + \pi \gamma$, which is the vector of derived processing request rate. Then processing request intensity at entity i is $\rho_i = \pi_i / \mu_i$ and $\rho_i < 1$ for the system to be in the equilibrium.

Based on the Jackson network assumption, we have a simple closed form solution of the distribution of knowledge combination work in process at all entities [20,21]:

$P(k_1, k_2, \dots, k_N) = \prod_{i=1}^N \rho_i^{k_i} (1 - \rho_i)$ and Q_i , the average number of knowledge work in process and in the waiting at i , is $Q_i = \rho_i / (1 - \rho_i)$. The throughput of knowledge combination process stored at knowledge base B is π_B .

6. Implications of the model and its performance measures in knowledge management

We show that the mapping itself reveal important points which were not recognized by other approaches such as social network analysis technique. In addition, performance measures to be obtained from the analysis provide some insights to managerial and social considerations.

Applying the Jackson assumption to the model is an approximation. However, the model along with the analyses, which we call engineering science, convey the following implications to management and social sciences.

First, the matrix γ itself involves the decision by an entity to rely on other entities for knowledge augmentation. The ideal case is to choose the best entity to get help. But as an organization gets bigger and the turnover rate of the members is higher, the actual γ should be much different from the ideal case. Well designed people locating system would provide good

information for this. If there is no request of knowledge combination, the model is not triggered at all. λ may be left to entities for autonomous inputs if their initiatives are active enough. However, if they are not, an incentive system may be introduced or a pre-planned λ can be pushed by management. As was discussed in section 3, λ can be induced either from the inside or outside of an organization. From the inside, they can be generated from total quality management circles and from the needs of innovation. From the outside, they can come from government policy, benchmarking, and case studies and by attending conferences and trade fairs. To increase λ , the role of boundary spanner [16] is crucial.

The intensity, ρ_i , is the ratio for an entity to handle the request, compared with its capacity for processing. If ρ_i is approaching to 1, the number of knowledge in process can grow exponentially. When ρ_i , for all i , is sorted in descending order, we can notice the entities overloaded and lightly loaded. The reasons of overloading come from either high initiation of knowledge requests or other entity's reliance on that entity. The management needs to look into details to see the intrinsic reason. Overloading may cause burnout of the overloaded entity and degradation of knowledge produced.

The number of organizational knowledge produced during a certain period of time, or throughput, is important for a company under the pressure of continuous innovation. If a company has competitive edge, the company needs to generate the knowledge when and where it is required. Davenport [22] brought the just-in-time (JIT) concept into knowledge management area. If the throughput to organizational knowledge base π_B is low, the organization cannot deliver the knowledge needed in the JIT way, making the organization's competitive edge lagging. In manufacturing settings, the level of inventory including work in process is one of the most crucial managerial concerns. Likewise, the number of knowledge works in inventory needs to be under managerial attention.

7. Conclusions

We brought in engineering science into knowledge

combination process which has been studied from either management or social perspective.

For this purpose we proposed an integrative model of knowledge combination process which includes knowledge combination entities, a knowledge base, and a knowledge base gatekeeper, and their interactions. We also applied a network of queues for analyzing the model. Even though the Jackson network used approximates the model, it provides a set of valuable implications such as the parameters themselves and performance measures such as the average number of knowledge combination in process at each entity, the rate of knowledge throughput to knowledge base.

From these quantitative measures, managerial and social decision regarding knowledge management can be further enhanced.

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<Research Interests>

Network application, Knowledge Management, Trust in Network Environment