Assessing the contribution of knowledge to business performance: 
the KP$^3$ methodology

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Abstract

Knowledge is inherently difficult to measure. However, without valid and reliable measurement, it is very difficult to develop a comprehensive theory of knowledge and provide a practical guide for knowledge management. In this paper, we do not measure knowledge directly, but assess how much knowledge contributes to business performance. The KP$^3$ methodology developed in this paper assesses the contribution of knowledge to business performance by employing product and process as intermediaries between the two. The understanding of the contribution is essential because it makes it possible to assess the productivities of knowledge entities, evaluate and compensate knowledge workers, and to allocate and develop human capital.

Keywords: Measurement of knowledge; Knowledge management; KP$^3$ methodology; Data envelopment analysis; Employee evaluation and compensation

1. Introduction

Knowledge is considered one of the most important assets in the economy. It is the major source of economic growth of the country and of the success of individual corporations [3]. The importance of knowledge has become even more emphasized as industrial economies enter a new epoch involving the new economies. Regarding the importance of knowledge, Peter Drucker [11] mentioned in his book, *Managing in a Time of Great Change* that “knowledge has become the key economic resource and the dominant—and perhaps even the only—source of competitive advantage”. Because knowledge is difficult to create and imitate, it can be an important source of sustainable competitive advantage [30,32,37]. Therefore, it has to be nurtured and managed [23,25,27].

For effective knowledge management, it is very important to measure knowledge. Without valid and reliable measurement, it becomes very difficult to develop a comprehensive theory of knowledge or knowledge assets. Consequently, no clear progress can be made in the efforts to treat knowledge either as a variable to be researched or asset to be managed [14]. However, the inherently intangible characteristic of knowledge makes its measurement difficult. In fact, on a survey of 431 US and European organizations, 43% of the respondents replied that measuring value and performance of knowledge assets is the most difficult thing next to the changing people’s behavior [35].
In our paper, we take a different approach to "measure" knowledge. That is, we try not to directly measure knowledge, which may either not exist or cannot be measured. Instead, we assess how much each entity of knowledge contributes to the actual business performance. Using business performance data, which is the result of applying knowledge to business operations, the methodology developed in this paper enables to assess the contribution of each knowledge entity to business performance. Specifically, knowledge contribution to the business performance was estimated using the Data Envelopment Analysis (DEA) approach to find the ideal composition of knowledge entities for the most efficient production of business performance.

The assessment of knowledge contribution to business performance provides an important understanding of the productivities of organizations and knowledge entities. Specifically, the assessment would highlight very useful information for evaluating and compensating knowledge workers, and allocating and developing human capital depending on the business needs. As long as we understand, this is the first approach to assess the contribution of knowledge to the business performance.

The rest of the paper is organized as follows. In Section 2, the background of the methodology is explained. The components and relationships among them are explained in Section 3. In Section 4, linkage matrices are estimated using the DEA approach. Then, in Section 5, some important applications of the KP3 methodology are suggested and discussed. We conclude in Section 6 with an agenda for further research.

2. Background

Even though knowledge is one of the most important assets and ultimately related to better business performance, the effort to measure knowledge, especially to measure the contribution of knowledge to business performance has been less clear. Despite the fact that many companies recognize the importance of the tie between knowledge and business performance, thus far, few if any companies have been able to establish an explicit causal link between them, regardless of how it is measured [7]. It still remains as a major research agenda [38].

In fact, it is not clear whether knowledge can be measured or not [22]. Despite the various studies trying to develop metrics and models to measure knowledge [10,12,21,22,34], people think that measurement is one of the most difficult parts of the knowledge management activities [35]. Other studies even argue that knowledge cannot be measured, but the activities or outcomes associated with applying knowledge can be measured [8].

The methodology developed in this paper enables to assess the contribution of knowledge entities to business performance. The methodology, called the KP3 methodology, establishes logical links between knowledge and business performance through product and process concepts, and suggests various application areas for improving business performance. A number of linkage matrices were introduced for that purpose. With the help of those linkage matrices, the contribution of knowledge to business performance can be assessed. Because the direct link between knowledge and business performance and its assessment are difficult from the perspective of practical implementation, a two-step approach was proposed by employing Product and Process as intermediaries.

One of the major building blocks of the KP3 methodology is knowledge. In fact, knowledge is viewed from many different perspectives. Nonaka and Takeuchi [29] suggested two types of knowledge: tacit knowledge and explicit knowledge. Collins [4] related knowledge types to their accessibility: symbol-type knowledge, embodied knowledge, embrained knowledge, and encultured knowledge. There are other views on knowledge types, which include Van der Spek and Spijkervet [40], Quinn et al. [33], etc. In the framework of the KP3 methodology, knowledge helps to achieve business performance through product and process. It is our view that product and process serve as key intermediaries when we want to relate knowledge to performance, and accordingly the associated knowledge should be managed by **Product knowledge** and **Process knowledge**.

To assess business performance, financial performance and organizational performance were used in this paper. Incidentally, several research findings in the area of human resource management show that human resources increase the financial and organizational performance and serve as the source for sustainable
In a study, which assesses the impact of human resource management practices on the business performance, Harel and Tzafrir [16] used similar performance measures: organizational performance and market performance in relation to the company’s competitors. The assessment of the contribution of knowledge and the measurement of the impact of human resource management practices share common characteristics. They both involve the assessment of the contribution of human capital. Therefore, financial and organizational performance could be used to measure the contribution of knowledge to business performance.

3. The KP³ methodology

3.1. The approach

Fig. 1 shows the overview of the KP³ methodology. The basic building blocks of the KP³ methodology consist of four components: Knowledge, Process, Product, and Performance. Knowledge is further classified into two: product-related knowledge and process-related knowledge.

The arrows in Fig. 1 with solid lines represent the fact that the four components are linked together through four linkage matrices: the Knowledge–Product matrix, the Product–Performance matrix, the Knowledge–Process matrix, and the Process–Performance matrix. The purpose of the linkage matrices is to link knowledge to business performance through product and process. Specifically, product knowledge is linked to product by the Knowledge–Product matrix and further linked to financial performance by the Product–Performance matrix. On the other hand, process knowledge is linked to process by the Knowledge–Process matrix and further linked to organizational performance by the Process–Performance matrix. Process and organizational performance are indirectly linked to product and financial performance, respectively, and the linkages are represented as dotted lines.

It is important that the four components in the KP³ methodology are linked logically. The logical linkage would enable the monitoring of the status of financial and organizational performance, and it would take necessary actions to improve them through knowledge management activities. The solid line in Fig. 1 represents presumably direct relationships that can be formally stated with logical or mathematical expressions. It means that the contributions of knowledge are possibly quantified and monitored so as to influence them to improve business performance. The dotted line represents indirect relationships that exist but cannot be expressed explicitly. It means that it is hard to measure organizational contribution in monetary terms and their influence is rather indirect.

![Fig. 1. Overview of the KP³ Methodology.](image-url)
In the next section, four components of the KP3 methodology (knowledge, process, product, and performance) and four linkage matrices (the Product–Performance matrix, the Process–Performance matrix, the Knowledge–Product matrix, and the Knowledge–Process matrix) are explained in more detail.

3.2. Components of the KP3 methodology

3.2.1. Knowledge

According to Nonaka and Konno [28], knowledge is created in a knowledge platform emerged in individuals, working groups, project teams, informal circles, temporary meetings, e-mail groups, and at the frontline contact with the customer. According to them, two typical forms of knowledge are created and shared among organizational members. Explicit knowledge is a type of knowledge which can be formed and expressed as data, scientific formulae, specifications, manuals and the like, while tacit knowledge is another type which is highly personal and hard to formalize like subjective insights, intuitions and hunches.

In the framework of the KP3 methodology developed in this paper, knowledge helps to achieve business performance through product and process. It is necessary to classify knowledge not only from the knowledge type (tacit and explicit) but also from the knowledge domain (product-related and process-related). Therefore, knowledge can be classified into four categories using product and process as the entities of the second dimension, in addition to the first dimension of knowledge type (tacit and explicit knowledge). Fig. 2 depicts our knowledge classification scheme. It is different from the conventional one in that it provides us with a vehicle to relate knowledge to performance via product and process as intermediaries.

In a knowledge-intensive firm, product is the explicit output of the value-adding activities or production process in the organization, while process is the procedure which transforms information and knowledge inputs into an explicit output in an efficient way. Hence, product knowledge tends to be more object-oriented, focused on a specific product, while process knowledge is relatively more collective. Referring to Nonaka and Konno’s [28] terminology, tacit product knowledge constitutes the technical dimension, while tacit process knowledge shapes the cognitive dimension.

Specifically, we can associate the four categories of knowledge with more concrete forms. As shown in Fig. 1, tacit product knowledge is product-specific know-how that cannot be easily expressed, and it resides in the human brain. On the other hand, tacit process knowledge is human capability that enables the efficient value-adding process, and it resides in the human brain and culture. Regarding the explicit knowledge, explicit product knowledge is the knowledgebase accumulated in a knowledge repository focusing on a specific product. Explicit process knowledge is workflow embedded in an IT-based workflow system.

Explicit knowledge is knowledge that can be more easily found or brought in from internal or external sources than tacit knowledge which is contained in the human brain or culture. For the purpose of knowledge management, we focus on tacit rather than explicit knowledge in the KP3 methodology. Therefore, when we mention product or process knowledge, we mean tacit product knowledge or tacit process knowledge more specifically.

Product knowledge is knowledge directly related to the company’s specific product. Based on the studies by Hall [15], Day [9], and Hitt et al. [17], we identify in this paper three key product knowledge entities: (1) Technology-related, (2) Operations-related, and (3) Market-related. Technology-related product knowledge includes manufacturing know-how and understanding of technical functions for a specific product like semiconductor, medicine, software, contents, and so on. Operations-related product knowledge is related with the value chain activities for a specific product. According to Hall [15], it is considered the most important area of employee know-how. Finally, market-related product knowledge is product-specific
know-how or understanding in relation to the behavior of the suppliers, competitors, and customers.

Process knowledge is the knowledge associated with the activities performed in each stage of a value chain from inbound logistics to customer care. Compared to product knowledge, which is directly related to the provision of products or services, process knowledge is a kind of glue that brings the organizational knowledge assets together and enables the achievement of better financial and organizational and market performance [9]. A number of studies deal with various types of human capability or tacit process knowledge in our terms. They include problem solving, problem finding, prediction, social interaction [20], leadership expertise, social judgment skills [5], learning capabilities [24], and political skill [13]. Based on the previous studies, we identify four key process knowledge entities: (1) leadership capability, (2) problem-solving capability, (3) communication capability, and (4) learning capability.

3.2.2. Product

Products are the output of the value chain activities. If the company or organization in discussion were a service company, product would mean service in that context. For each product, we assume that there is a product division responsible for it.

3.2.3. Process

The process of delivering a product or service can be divided into a number of linked activities, each of which adds values for customers [31]. The value chain is a framework for analyzing the contribution of each activity to the business performance. Various activities that make up the value chain are important individually, but they are perhaps even more important in combination. Overall, value for customer is created not by individual value chain activities but by groups of activities that come together to form what are known as core processes [26]. Miller and Dess [26] consider three processes: (1) product development process, (2) demand management process, and (3) order fulfillment process as core processes. Based on their studies, we identify them as core processes.

Because the core processes are sets of critically important activities that produce products and eventually determine the performance of a company, they need to be well managed. Process knowledge would make the core process the most efficient and productive contributor to both the financial and organizational performance.

3.2.4. Performance

Performance or business performance is both financial and organizational. Financial performance is directly influenced by how the product or service performs in the market. Depending on the characteristics of the product and service, different metrics can be used. The typical monetary metrics for measuring financial performance are revenue, Economic Value Added (EVA), profit, etc. Especially, financial performance is considered quite essential considering the fact that real financial improvement has to be demonstrated before the knowledge management activities are adopted and diffused in the regular business activities.

Meanwhile, organizational performance is usually defined with nonmonetary metrics, thus it is relatively difficult to measure. Though it could be measured indirectly using some “intermediate” measures like the number of new ideas, the number of new products, and job satisfaction level, the contribution of knowledge management activities to the organizational performance is hard to be translated into tangible benefits. Organizational performance is as important as financial performance because the organizational quality would indirectly influence financial performance serving as a moderating factor.

3.3. Linkage matrices

The four components of the KP³ methodology need to be linked logically. To represent the relationships of knowledge to business performance over product and process, four linkage matrices are employed to link four components of the KP³ methodology. They are the Knowledge–Product matrix, the Product–Performance matrix, the Knowledge–Process matrix, and the Process–Performance matrix. Knowledge–Product matrix links from product knowledge to product, Product–Performance matrix links from product to financial performance, Knowledge–Process matrix links from process knowledge to process, and Process–Performance matrix links process to organizational performance. We explain each matrix in detail.
3.3.1. Knowledge–Product matrix

The knowledge in the Knowledge–Product matrix is basically product-related. Let us represent individual p’s Knowledge–Product matrix as $A(p)$. Then, $A(p) = [a_{ij}(p)]$, where $a_{ij}(p)$ is defined as the level of product knowledge $i$ employee $p$ has accumulated in association with product $j$. The value $a_{ij}(p)$ is assessed to be $0 \leq a_{ij}(p) \leq 1$, and $a_{ij}(p) = 1$ if employee $p$ is an expert in product knowledge $i$ related to product $j$.

Product knowledge can be measured for each individual at a certain point of time and later updated regularly or on an ad hoc basis. To measure the level of product knowledge, we devised an eleven-scale measure as shown in Table 1. It can be customized depending on the application domain.

Because knowledge level is defined to be additive, we can add individual knowledge to estimate the knowledge stock or input in any organizational level.

If we denote an organization by a set of people $\Omega$, the knowledge stock of the organization $\Omega$ is estimated by adding each individual’s knowledge stock. That is, the product knowledge stock as a whole is represented by

$$A(\Omega) = \sum_{p \in \Omega} A(p) = \left[ \sum_{p \in \Omega} a_{ij}(p) \right].$$

3.3.2. Product–Performance matrix

Performance in the Product–Performance matrix is usually a financial performance, which is achieved by the knowledge activities. Let us represent Product–Performance matrix as $B$ matrix. Also, let $FP_k(\Omega_j)$ be the financial performance for performance metric $k$, which the product division $\Omega_j$ has achieved for some period of time. Then, $B = [b_{jk}]$ can be obtained by $b_{jk} = (FP_k(\Omega_j))/(\sum_i \sum_{p \in \Omega} a_{ij}(p))$. The value $b_{jk}$ can be interpreted as the knowledge productivity of the product division $\Omega_j$ in terms of financial performance metric $k$.

Though, we define the knowledge productivity in an aggregate level, one might be interested in the knowledge productivity defined for each knowledge entity. We will discuss it in Section 4.

3.3.3. Knowledge–Process matrix

The knowledge in the Knowledge–Process matrix is primarily process-related knowledge. Let us represent individual p’s Knowledge–Process matrix as $U(p)$. Then, $U(p) = [u_{lm}(p)]$, where $u_{lm}(p)$ is the level of process knowledge $l$ employee $p$ has accumulated in association with core process $m$. The value $u_{lm}(p)$ is assessed to satisfy $0 \leq u_{lm}(p) \leq 1$, and $u_{lm}(p) = 1$ if an employee $p$ is an expert in process knowledge $l$ related to the core process $m$.

The knowledge in the Knowledge–Process matrix can also be assessed as the knowledge stock or input in any organizational level, team or larger business unit, as well as an individual capability rating for a particular employee. The matrix can be measured and updated in the same way as the Knowledge–Product matrix.

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**Table 1**

Eleven-scale rating for the knowledge level assessment

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Complete ignorance</td>
</tr>
<tr>
<td>0.1</td>
<td>Needs fundamental education and constant supervision</td>
</tr>
<tr>
<td>0.2</td>
<td>Very poor and little hope for improvement</td>
</tr>
<tr>
<td>0.3</td>
<td>Poor and needs significant development</td>
</tr>
<tr>
<td>0.4</td>
<td>OK with constant guidance, and it could become satisfactory with more experiences</td>
</tr>
<tr>
<td>0.5</td>
<td>Satisfactory and can perform a job requiring the skill satisfactorily with some support from the colleagues having some experience</td>
</tr>
<tr>
<td>0.6</td>
<td>Good and can do any job requiring the knowledge successfully and independently</td>
</tr>
<tr>
<td>0.7</td>
<td>Very good and can do any job related to knowledge-intensive work successfully</td>
</tr>
<tr>
<td>0.8</td>
<td>Can perform know-intensive job not only independently but also can be a leader helping other people who need support</td>
</tr>
<tr>
<td>0.9</td>
<td>Excellent and expert-equivalent level which can be a mentor or role model for the knowledge related works</td>
</tr>
<tr>
<td>1</td>
<td>World class expert on the domain</td>
</tr>
</tbody>
</table>
3.3.4. Process–Performance matrix

The performance in the Process–Performance matrix means organizational performance. Let us represent the Process–Performance matrix as $V$ matrix. Also, let $\text{OP}_n(\Omega)$ be the organizational performance for performance metric $n$, which the functional organization $\Omega$ has achieved for some period of time. Then, $V=[v_{mn}]$ and the estimate of $v_{mn}$ is obtained by $v_{mn} = (\text{OP}_n(\Omega))/\sum_{p \in \Omega} u_{lm}(p)$. The value $v_{mn}$ can be interpreted as the knowledge productivity of the core process $m$ in terms of organizational performance metric $n$.

This matrix shows how each core process contributes to organizational performance. Because organizational performance is sometimes viewed differently for different processes, process-related performance metrics can be developed for each process depending on the management needs. Note that knowledge productivity in view of organizational performance can either be defined separately for each core process or in an aggregate level for a specific product division.

Table 2 shows examples of the organizational performance metric.

3.4. Linking knowledge to business performance

With the components of the KP3 methodology and its linkage matrices, contribution of product and process knowledge to the financial and organizational performance can be assessed. The estimates are highly valuable information in many management functions like human resource allocation, knowledge development, employee evaluation and compensation, etc. The potential applications are explained in Section 5.

### Table 2

Examples of organizational performance metric

<table>
<thead>
<tr>
<th>Process</th>
<th>Performance</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency</td>
<td>Quality</td>
</tr>
<tr>
<td>Product development</td>
<td>number of new products or new services developed</td>
<td>number of successful product launches</td>
</tr>
<tr>
<td>Demand management</td>
<td>service provisioning time</td>
<td>number of automated processes</td>
</tr>
<tr>
<td>Order fulfillment</td>
<td>number of processed customer calls</td>
<td>customer satisfaction index</td>
</tr>
</tbody>
</table>

3.4.1. Product Knowledge–Financial Performance matrix

Let us represent matrix $C$ as a matrix showing the relationship between product knowledge and financial performance. That is, $C=[c_{ik}]$, where $c_{ik}$ is the contribution of product knowledge $i$ to financial performance metric $k$. Matrix $C$ can be defined and estimated in any organizational level as well as for an individual employee.

Given a product knowledge stock $A(\Omega)$ estimated for an organization $\Omega$, the associated Product Knowledge–Financial Performance matrix $C(\Omega)$ can be calculated by multiplying matrix $A(\Omega)$ and $B$ or summing up $c_{ik}$ over all $p \in \Omega$. That is, $C(\Omega) = A(\Omega)B$ or $C(\Omega) = \sum_{p \in \Omega} C(p) = \sum_{p \in \Omega} A(p)B$. Note that the matrix multiplication is done in such a way that the financial performance is summed over all products, that is, $c_{ik}(\Omega) = \sum_{j} a_{ij}(\Omega)b_{jk}$ and $c_{ik}(p) = \sum_{j} a_{ij}(p)b_{jk}$.

3.4.2. Process Knowledge–Organizational Performance matrix

Let us represent matrix $W^m$ as a matrix showing the relationship between process knowledge and organizational performance for process $m$. That is, $W^m=[w_{ln}^m]$, where $w_{ln}^m$ is the contribution of process knowledge $l$ to the organizational performance metric $n$ for process $m$. Because the units of organizational performance metrics could be different for each core process, their estimates cannot be added over processes as was done in Product Knowledge–Financial Performance matrix.

The matrix $W^m$ for each process $m$ can be calculated by multiplying two terms. That is, $w_{ln}^m = u_{lm}v_{mn}$ for a specific $m$. If we evaluate these measures at the individual employ level, it is obvious that $w_{ln}^m(p) = u_{lm}(p)v_{mn}$. The Process Knowledge–
Organizational Performance matrix in an organizational level, denoted by $W^m(\Omega)$, is easily obtained by adding each element over all employees in $\Omega$ or $W^m(\Omega) = \sum_{p \in \Omega} W^m(p) = \left[ \sum_{p \in \Omega} W^m_p(p) \right]$.

4. Estimating the linkage matrices

The KP$^3$ methodology suggested in the previous section is conceptually well structured, but estimating linkage matrices can be a bottleneck for the popular applications of the methodology. Especially $B$ matrix and $V$ matrix are hard to estimate. In this paper, we use Data Envelopment Analysis (DEA) approach to address this problem.

4.1. Data envelopment analysis

Data envelopment analysis, originally developed by Charnes et al. [2], is an application of linear programming that has been used to measure the relative efficiency of operating units with the same goals and objectives [6,36]. The operating units of most organizations have multiple inputs as well as multiple outputs. For our purpose of estimating linkage matrices, DEA can be effectively used to find the most productive composition of knowledge entities for an organizational unit of our interest.

Let us consider a telecommunications service provider, which provides mobile data services across the country. Because the mobile data service market is still in an early stage of development, the market demand is unpredictable. To be the leader in the market, major focus of the business activity needs to be the fast service development to satisfy ever-changing market needs. Therefore, market intelligence and industry understanding is considered very important. We are interested in finding the most productive knowledge composition by using the DEA approach in the framework of KP$^3$ methodology.

In order to focus on the estimation procedure itself, we assume that four regional centers in the company produce a single product, for example data service. For each regional center, the CEO wants to evaluate the knowledge productivities for the revenue from the data service (financial performance) and the number of service enhancements (organizational performance). Table 3 shows the relevant data for the analysis such as the number of employees, measured knowledge stock levels and achieved financial and organizational performances for a specific year.

The purpose of the DEA application is to find the most productive knowledge composition and linkage matrices. In Section 3, we explained the KP$^3$ methodology with linkage matrices, $A$, $B$, $C$ for product-related matrices, and $U$, $V$, $W$ for process-related matrices. However, for the purpose of simplicity, we handle product and process concept together, focusing on $A$, $B$ and $C$ matrices. That makes the following explanations simple.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Data for the analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organizational unit (Regional center)</td>
<td>RC-1</td>
</tr>
<tr>
<td>Number of employees</td>
<td>243</td>
</tr>
<tr>
<td>Product knowledge</td>
<td></td>
</tr>
<tr>
<td>Technology-related knowledge</td>
<td>102</td>
</tr>
<tr>
<td>Operations-related knowledge</td>
<td>85</td>
</tr>
<tr>
<td>Market-related knowledge</td>
<td>85</td>
</tr>
<tr>
<td>Process knowledge</td>
<td></td>
</tr>
<tr>
<td>Leadership capability</td>
<td>66</td>
</tr>
<tr>
<td>Problem solving capability</td>
<td>92</td>
</tr>
<tr>
<td>Communication capability</td>
<td>129</td>
</tr>
<tr>
<td>Learning capability</td>
<td>70</td>
</tr>
<tr>
<td>Financial performance</td>
<td></td>
</tr>
<tr>
<td>Value-added from data service (unit: 100,000 dollars)</td>
<td>778</td>
</tr>
<tr>
<td>Organizational performance</td>
<td></td>
</tr>
<tr>
<td>Number of service enhancements</td>
<td>51</td>
</tr>
</tbody>
</table>
We can estimate the most productive knowledge composition for regional center 1 (RC-1) by solving the following DEA problem.

\[
\begin{align*}
\text{Min } & \quad e_1 \\
\text{subject to } & \quad 102w_1 + 71w_2 + 85w_3 + 83w_4 - 102e_1 \leq 0 \\
& \quad 85w_1 + 71w_2 + 76w_3 + 85w_4 - 85e_1 \leq 0 \\
& \quad 85w_1 + 60w_2 + 78w_3 + 77w_4 - 85e_1 \leq 0 \\
& \quad 66w_1 + 47w_2 + 58w_3 + 72w_4 - 80e_1 \leq 0 \\
& \quad 92w_1 + 62w_2 + 78w_3 + 80w_4 - 92e_1 \leq 0 \\
& \quad 129w_1 + 95w_2 + 103w_3 + 106w_4 - 129e_1 \leq 0 \\
& \quad 70w_1 + 47w_2 + 52w_3 + 72w_4 - 70e_1 \leq 0 \\
& \quad 778w_1 + 624w_2 + 650w_3 + 929w_4 - 778e_1 \leq 0 \\
& \quad 51w_1 + 80w_2 + 60w_3 + 75w_4 - 51e_1 \leq 0 \\
& \quad w_1 + w_2 + w_3 + w_4 = 1 \\
& \quad w_1, w_2, w_3, w_4, e_1 \geq 0,
\end{align*}
\]

where \( w_i \) is the weight applied to inputs and outputs for RC-\( i \), \( i = 1, 2, 3, 4 \), and \( e_1 \) (efficiency index for the RC-1) is the fraction of RC-1’s input required by the composite regional center.

If we solve the optimization problem (Eq. (1)), we get the optimal solution, \( w_1^* = 0, w_2^* = 0.49508, w_3^* = 0, w_4^* = 0.50492 \), and \( e_1^* = 0.91846 \). It tells us that RC-1 can be more efficiently operated by the combination of RC-2 and RC-4 with weights \( w_2^* = 0.49508 \) and \( w_4^* = 0.50492 \).

Currently, RC-1 is less efficient than the hypothetical composite regional center with efficiency index \( e_1^* = 0.91846 \). It means that with the optimal knowledge input composition, the composite regional center can produce 778 units of value added and 77 service enhancements with only 91.8% or less knowledge input from the RC-1. More detailed analysis tells us that the constraint associated with the operations-related knowledge is the binding constraint. It implies that the operations-related knowledge is most efficiently used, and other knowledge entities are not.

Based on the above result, we can estimate matrices \( A \), \( B \), and \( C \) associated with the most productive hypothetical regional center. Fig. 3 shows the estimated matrices.

\[
\begin{bmatrix}
77 & 1.512 & 0.151 \\
78 & 117 & 12 \\
69 & 118 & 12 \\
60 & 104 & 10 \\
71 & 90 & 9 \\
101 & 107 & 11 \\
60 & 152 & 15 \\
\end{bmatrix}
\]

Fig. 3. Estimated matrices, \( A \), \( B \), and \( C \).

The most productive knowledge composition represented by the column matrix \( A \) can be obtained by combining the knowledge inputs for RC-2 and RC-4 with weights \( w_2^* = 0.49508 \) and \( w_4^* = 0.50492 \), respectively. Because the most productive hypothetical regional center can produce 778 units of value added and 77 service enhancements using the total 514.6 knowledge inputs, we can estimate that 1 unit of knowledge input can produce 1.512 unit of financial performance and 0.151 unit of organizational performance. The first and second columns of the \( C \) matrix are the contribution of knowledge to the financial and organizational performances, respectively.

The estimation of linkage matrices for this hypothetical center enables us to evaluate the actual knowledge productivities of each knowledge entity. We deal with this issue in the next section.

4.2. Assessing knowledge productivities

In performing knowledge management activities, knowledge productivity for each knowledge entity provides valuable information. In this section, we show how the DEA output obtained in the previous section can be used to estimate them.

4.2.1. Knowledge productivity of organizations

Not only for RC-1, but we can formulate three more DEA problems associated with each regional center and solve them to find the associated most productive centers. Table 4 summarizes the optimal solutions for those four DEA problems.

From Table 4, we can see that input knowledge compositions for RC-2 and RC-4 do not need to be changed. However, knowledge input compositions for
4.2. Knowledge productivity of knowledge entity

From the DEA output, we can estimate the knowledge contribution of each knowledge entity to business performance. The actual knowledge input composition and decomposed performance can be represented by matrices $A_{\text{actual}}$ and $C_{\text{actual}}$.

$$A_{\text{actual}} = \begin{bmatrix} 102 \\ 85 \\ 92 \\ 70 \end{bmatrix}, \quad C_{\text{actual}} = \begin{bmatrix} 117 & 8 \\ 118 & 8 \\ 104 & 7 \\ 90 & 6 \\ 107 & 7 \\ 152 & 10 \\ 90 & 6 \end{bmatrix}$$

For the optimal knowledge composition, we know that the knowledge productivities are same for all the knowledge entities. However, that is not the case for matrices $A_{\text{actual}}$ and $C_{\text{actual}}$. If we divide the contributed performance by the actual knowledge input for each knowledge entity, we can estimate the individual knowledge productivity. By comparing these individual knowledge productivities with matrix $B=[1.512 \ 0.151]$, we can evaluate the relative productivities of knowledge entities for RC-1. The results are summarized in Table 5.

<table>
<thead>
<tr>
<th>Knowledge type</th>
<th>Knowledge entity</th>
<th>Actual knowledge productivity</th>
<th>Relative productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product knowledge</td>
<td>Technology-related knowledge</td>
<td>1.142, 0.075</td>
<td>0.755, 0.497</td>
</tr>
<tr>
<td></td>
<td>Operations-related knowledge</td>
<td>1.389, 0.091</td>
<td>0.918, 0.605</td>
</tr>
<tr>
<td></td>
<td>Market-related knowledge</td>
<td>1.220, 0.080</td>
<td>0.807, 0.531</td>
</tr>
<tr>
<td>Process knowledge</td>
<td>Leadership capability</td>
<td>1.366, 0.090</td>
<td>0.903, 0.595</td>
</tr>
<tr>
<td></td>
<td>Problem solving capability</td>
<td>1.168, 0.077</td>
<td>0.773, 0.509</td>
</tr>
<tr>
<td></td>
<td>Communication capability</td>
<td>1.178, 0.077</td>
<td>0.779, 0.513</td>
</tr>
<tr>
<td></td>
<td>Learning capability</td>
<td>1.288, 0.084</td>
<td>0.852, 0.561</td>
</tr>
</tbody>
</table>

From this information, we can see that operations-related knowledge is most efficiently used and other knowledge inputs are less efficient. This information can be used as a guideline to reallocate knowledge resources to improve business performance.

5. Applications

$\text{KP}^3$ methodology can be applied to many areas in business management. What follows are examples of its potential applications.

5.1. Employee evaluation and compensation

Based on the knowledge assessments and their potential contributions to business performance, we can evaluate and compensate employees. For example, we can evaluate employee $p$ based on $c_{ik}(p)$, which measures the contribution of his or her product knowledge $i$ to the financial performance metric $k$. In the same way, we can evaluate employee $p$ based on the $w_{ln}(p)$, which measures the contribution of his/her process knowledge $l$ to the organizational performance metric $n$ for process $m$.

With the information, we can design a criterion for evaluating employees. Let us assume that we would like to evaluate an employee $p$ in product division $j$ whose task is associated with process $m$. Then we could develop an evaluation score which is based on the financial performance metric $k$ and the organizational performance metric $n$ as follows:

$$e_{kn}(p) = a_k \sum_i c_{ik}(p) + \beta_{mn} \sum_i w_{ln}(p),$$

where $a_k$ and $\beta_{mn}$ are the weights for trading off financial and organizational performance. By setting
and dependent on the business objectives, we can encourage people to acquire and develop knowledge that the company needs the most to perform its management activities. Many variations of $e_{kn}(p)$ can be defined with varying degrees of aggregation, depending on the purpose of the employee evaluation.

5.2. Human resource allocation

With the knowledge management system set up in the company, linkage matrices represented by $A$, $B$, $C$, $U$, $V$, and $W$ would be available and updated regularly. This information can be used to allocate human resources to maximize business performance potential. Let us define a variable $x_j(p)$ in the following:

$$x_j(p) = \begin{cases} 
1 & \text{if employee } p \text{ is assigned to product division } j, \\
0 & \text{otherwise}
\end{cases}$$

Then, $\sum_p \sum_i a_{ij}(p)x_j(p)$ measures the aggregate level of product knowledge that the employees assigned to product division $j$ have in association with product $i$. Likewise, $\sum_p \sum_i u_{im}(p)x_j(p)$ is the aggregate level of process knowledge that the employees assigned to product division $j$ have in association with core process $m$.

Suppose that we want to allocate employees so as to maximize the expected financial performance $k$, while satisfying the requirement that the knowledge level for core process $m$ in product division $j$ needs to be above a certain level $\bar{u}_{mj}$. Then, the financial performance $k$ that the assigned employees are expected to achieve over all product divisions is $\sum_j b_{jk} \sum_p \sum_i a_{ij}(p)x_j(p)$ and the problem is formulated as

$$\text{Max } \sum_j b_{jk} \sum_p \sum_i a_{ij}(p)x_j(p)$$

s.t. $\sum_p \sum_i u_{im}(p)x_j(p) \geq \bar{u}_{mj}$ for all $m$ and $j$.

Different objectives with different set of constraints can be formulated in a similar way. Here are some examples. First, we can formulate the problem of maximizing the potential contribution to the organizational performance metric $n$, while satisfying the product knowledge requirement $\bar{b}_j$. Second, we can employ the multi-objective approach to formulate the problem of maximizing both the financial and organizational performance at the same time. Third, a more general and practical approach might be to formulate the problem of optimally trading off mutually conflicting financial and organizational performance. Also, other constraints can be easily incorporated into the formulation such as the minimum or maximum number of people assigned to a product division or personal preference for a product division.

5.3. Recruitment and human capital development

Suppose that objectives of a specific business unit are already setup and corresponding necessary knowledge requirements have to be understood. Matrix $A$, $B$, $C$, $U$, $V$, and $W$ can be used to assess the requirements for the process and product knowledge. The gap between the requirement and the real knowledge stock level can be used to plan some kind of employee training program in the company or to make specifications for employee recruitment.

5.4. Knowledge acquisition and administration

Once knowledge matrices $A$, $B$, $C$, $U$, $V$, and $W$ are measured, it is necessary to update them periodically to keep them current. Of course, the knowledge center should be responsible for it. Once the knowledge center infrastructure is well equipped with the database for implementing $KP^3$ methodology and an information network conveying that information, the company can easily find a person who is knowledgeable on any specific product domain or a particular skill with the help of the system. Furthermore, the company can prevent the company’s knowledge stock
from being obsolete by monitoring and upgrading the status of the knowledge stock at any of personal, divisional, or company levels.

6. Conclusions

Technological advances and changes in regulatory conditions are causing the world to quickly globalize. It has become almost impossible to imagine doing business without considering a global market. To be successful in the global market, knowledge should be managed as the most valuable asset of an organization.

For the successful management of knowledge, it has to be measured. However, it is not clear whether we can properly measure the knowledge for which either proper measurement may not exist or cannot be measured. To address this issue, we assessed the contribution of knowledge to business performance, rather than trying to measure the value of knowledge directly.

The KP³ methodology presented in this paper provides us with a way to assess the contribution of knowledge to business performance by employing product and process as intermediaries. This methodology is general enough to be applied to any industry with relevant domain knowledge. To assess the contribution of knowledge, optimal knowledge input composition is derived from the DEA approach and the information is used to assess the knowledge productivity of each organization and each knowledge entity.

Possible applications include employee evaluation and compensation, human resource allocation, recruitment and human capital development, knowledge acquisition and administration, project team building, knowledge map development, and career planning.

In order to implement the KP³ methodology successfully, several technical and managerial issues should be addressed in more detail. First, simple but effective knowledge classification schemes need to be further refined and measures for expertise or knowledge stock should be empirically validated. In this paper, we identified for the first time two aspects of knowledge, product knowledge and process knowledge, and decomposed them into mutually exclusive and collectively exhaustive knowledge entities. Though the suggested taxonomy is simple and good enough to be implemented in general business domains, more enhanced industry-specific or company-dependent classification schemes need to be developed depending on the application domains. Accordingly, various measures should be developed for them, along with adequate scales. Regarding the measurement of knowledge and its impact, research in the area of human resource management may provide some ideas [39,41].

Second, a proper incentive system for knowledge management activities has to be setup to help people buy into the KP³ methodology. Because extracting and sharing knowledge are not natural human behaviors, employees should be encouraged and motivated by proper incentives. The framework of the KP³ methodology will surely serve as an effective tool for the evaluation procedure too.

Third, the functions of the knowledge center as a KM supporting organization and even a Knowledge Management System (KMS) have to be more clearly defined and specified in detail before they can support the successful implementation of the KP³ methodology. Preliminary functions will include collecting knowledge from internal and external sources, classifying it for storage in a systematic way, and updating it periodically. Basic functions could be developed into a performance-oriented KMS and operated in close connections with employ evaluation and incentive systems. More advanced functions include knowledge auditing, proactive maintenance of knowledge classification schemes, and providing continuous feedback to various knowledge workers and/or knowledge managers.

As the speed of technological development increases and the body of accumulated data and information becomes ever larger, the value of knowledge and the need for knowledge management will continue growing. As far as we understand, the KP³ methodology is the first attempt assessing the contribution of knowledge to the business performance through product and process. This approach enables us to relate knowledge to business performance more explicitly and provides valuable insights on how to manage knowledge strategically. Eventually, KP³ methodology could provide a sustainable competitive advantage for the company that uses it.
Many theoretical and practical issues for the real-world applications of KP3 methodology still remain to be addressed. The application areas suggested in this paper can be extended and the optimal decisions can be characterized for each application based on the mathematical formulations. Empirical studies on some hypotheses derived from those characterizations will further validate the applicability and the usefulness of the methodology.

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