A Methodology for Collaborative Performance Measurement of Manufacturing Collaboration

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Abstract

Effective performance measures must be developed in order to effectively maintain successful collaboration. This paper presents a methodology of collaborative performance measures to evaluate the overall performance of a collaboration process between multiple manufacturing partners. The partners first define collaborative key performance indicators (cKPI), and they then measure the cKPIs and calculate the synthetic performance from the cKPI values to evaluate the result of the collaboration case. To measure different scales of cKPI, we develop a two-folded desirability function based on the logistic sigmoid functions. The proposed methodology provides a quantitative way to measure collaborative performance in order to effectively manage collaboration among partners, continuously improving collaboration performance.

Keywords: Manufacturing collaboration, performance measurement, collaborative key performance indicators, two-folded desirability function, sigmoid function.

1. Introduction

One important change in the manufacturing industry is that competition between individual companies has been extended to competition between the manufacturing networks surrounding the companies (NISA, 2001). This is because the competitive advantages of modern manufacturing companies are derived from manufacturing collaboration in virtual enterprise networks such as supply chains (Mun *et al.*, 2009). Most existing performance measures, however, have been developed to evaluate the performance of internal or outsourcing projects from the perspective of a single company (Ghalayini *et al.*, 1997; Khadem *et al.*, 2008; Koc, 2011). Moreover, some performance indicators such as trading costs are oriented to a single company, and cannot be directly applied to measuring the collaboration performance since such indicators conflict between two partners. As a result, new collaborative performance measures are needed so that collaboration partners can make arrangements and compromises with each other, reflecting their common interests.

In this paper, we first introduce the concept of collaborative key performance indicators (cKPIs), which are defined to measure the collaboration performance of multiple manufacturing partners. cKPIs are calculated by using several key performance indicators (KPIs) which individual partners can measure. For this research, we referred to the Supply Chain Operations Reference (SCOR) model (SCC, 2006) to define cKPI for manufacturing collaboration. Since the SCOR model provides corresponding performance metrics as well as several levels of supply chain process models, it can be a good reference for defining collaborative performance indicators (Barratt, 2004).

Published in International Journal of Industrial Engineering- Theory, Applications and Practice, Vol. 19, No. 3, Mar 2012, pp. 149-160.

In addition, we developed a two-folded desirability function to reflect the characteristics of performance indicators in manufacturing collaboration. The desirability function, which is based on the sigmoid function, can reflect multiple cKPI criteria in service level agreements (SLA). Further, unlike existing desirability functions, the sigmoid based desirability function can transform different scales of cKPIs into values between 0 and 1 without requiring maximum or minimum values (Lee and Yum, 2003). The weighted values of two-folded desirability functions for all cKPIs are summed to determine the synthetic performance of a collaboration, which can be compared with prior performance or partners' performance.
This paper is organized as follows. We first introduce the background of our research in Section 2. The framework of collaborative performance management is presented, along with the concept of cKPI, in Section 3. Subsequently, how to design the collaborative performance indicators and how to measure the performance indicators of manufacturing collaboration are described in Section 4 and Section 5, respectively. Finally, Section 6 concludes this paper.

2. Background

2.1 Collaboration in Manufacturing Processes

Manufacturing sector is a critical backbone of a nation's economy while other industries such as information and service sectors are rapidly emerging for economic growth in developed countries. In order for manufacturing enterprises, especially small and medium-sized corporate, to stay competitive, manufacturing collaboration can be a promising alternative since it can support them to gain benefits of internetworked communication through the Internet. For a success of effective manufacturing collaboration, a special care needs to be taken in the perspective of two key aspects: technical architecture in terms of collaboration support functionalities and managerial support in terms of collaborative performance measurement and analysis.
Considering small and medium-sized manufactures could not afford to purchase expensive proprietary software nor invest a large amount of budget in constructing and operating their own information system to support collaboration with other partners, it is necessary to build an infrastructure that can connect them by providing essential functionalities with economical cost. To meet this need, an effort has been taken to develop a collaboration network system for manufacturing partners from product planning to development, design, purchase, production, and services since 2005 (http://www.i-mfg.com/). About 600 small and medium-sized manufacturers are currently connected by the developed system, and they have achieved cost reduction and productivity increase (Lee, 2007). It has put focus on four key facets: information innovation, manufacturing process innovation, manufacturing system innovation, and new product development innovation. The detailed structure of the manufacturing collaboration infrastructure is illustrated in Figure 1 (Lee, 2007).

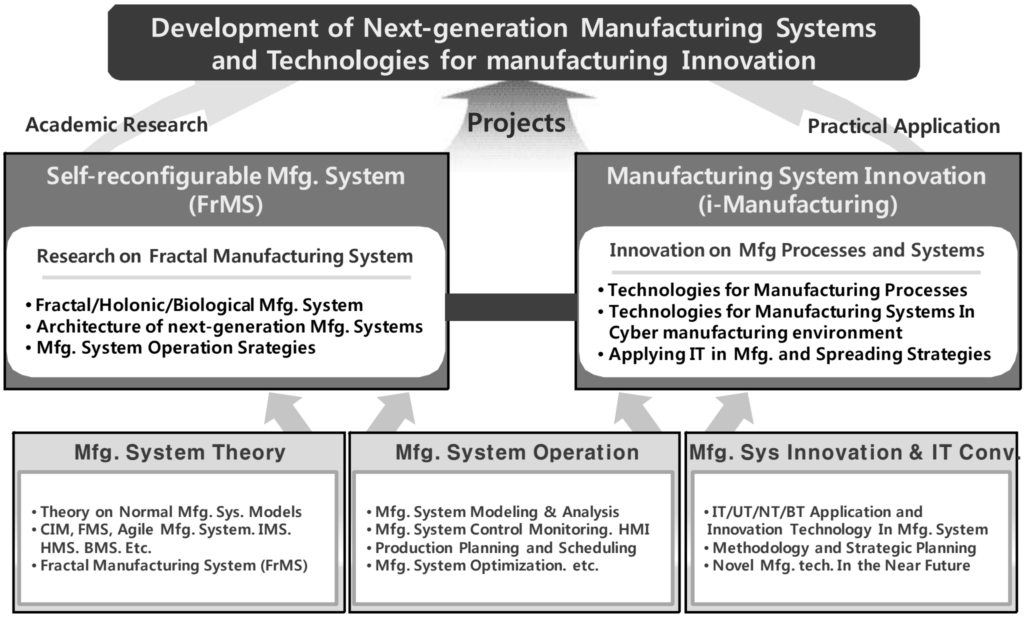


Figure 1. The framework of manufacturing collaboration infrastructure

In addition to providing an infrastructure with technically validated functionalities, management of performance related to manufacturing collaboration is another key aspect for effective proliferation of collaboration. All the stakeholders including top management in collaboration partner enterprises need to be convinced that they can gain benefits through collaboration in their manufacturing processes. To this end, a methodology of collaborative performance measurement and analysis should be established.

2.2 Collaborative Performance Measurement

Next we review previous work in collaborative performance measurement. Busi and Bititci (2006) highlight the significance of collaborative performance management in their survey paper. The concept of collaborative key performance indicators was proposed by Akkermans and van Oppen (2006) to leverage the collaboration between buyers and sellers. Taticchi *et al.* (2009) present a hierarchical approach to collaborative performance measurement and management.

Much research on collaborative performance measurement considers supply chain management (Brewer and Speh, 2000; Shin *et al.*, 2000; Min and Park, 2003, 2009; Forslund *et al.*, 2009). In the meantime, various collaboration performance indicators have been developed for supply chain management. Guinipero (1995) suggests that the evaluation criteria for service providers change from traditional indicators such as on-time delivery rate, error rate, cost reduction rate, and cycle time into extended indicator aspects such as new part development rate, total cost reduction, and total processing time reduction. Wheelwright and Bowen (1996) present performance indicators for supply chain management including cost, quality, delivery period, and flexibility. Gill and Abend (1997) propose measuring distribution efficiency, cost reduction of the supply chain, reduction of inventory, and the reduction of lead time. Shin *et al.* (2000) present several measures of provider performance such as lead time, timely delivery, reliability of delivery, quality, and cost, while suggesting quality, delivery, cost, and flexibility as measures of buyer performance.

Rather than developing primitive performance indicators, some research uses performance measurement and management frameworks such as Balanced Scorecard (BSC) and the SCOR model. Brewer and Speh (2000) combine the main goals of supply chain management with BSC to enable performance evaluation of supply chains. Niebecker *et al.* (2008) also adopt BSC for measuring the performance of collaborative projects. Meanwhile, several studies applied the SCOR model for the performance measurement of supply chain process. Min and Park (2003) introduce performance measurement of the supply chain and systemized their measures with the SCOR model. Shin and Hong (2007) also propose their performance measurement framework for supply chain management on the SCOR model.

2.3 Desirability Function

Desirability functions have been applied to manufacturing process to transform the measured values of process variables into desirability values between 0 and 1 (Fuller and Scherer, 1998). Kim and Lin (2000) devise a non-linear desirability function based on exponential functions. The desirability can be calculated from the response variables as follows:

$$d(z) = \begin{cases} \frac{e^t - e^{t|z|}}{e^t - 1}, & if \quad t \neq 0 \\ 1 - |z|, & if \quad t = 0 \end{cases} \tag{1}$$

Response variables are assumed to be classified into LTB (Larger-The-Better), STB (Smaller-The-Better), and NTB (Normal-The-Best). To measure the desirability of the three types of response variables, the z value is first calculated by using the response value Y with the maximum, minimum, and target response values, noted as Y_{max}, Y_{max}, and T, respectively (Kim, and Lin, 2000). Figure 2 shows the shapes of exponential desirability functions according to their t value.

$$z = \begin{cases} (Y_{\max} - Y)/(Y_{\max} - Y_{\min}) & if \ Y \ is \ LTB \\ (Y - Y_{\min})/(Y_{\max} - Y_{\min}) & if \ Y \ is \ STB \\ (Y - T)/(Y_{\max} - T) = (Y - T)/(Y_{\max} - T) & if \ Y \ is \ NTB \end{cases} \tag{2}$$

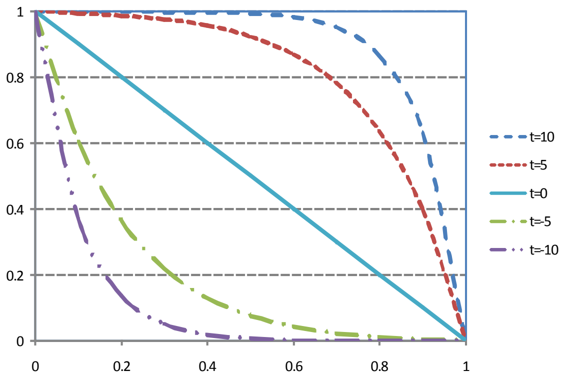


Figure 2. The shapes of exponential desirability functions according to their *t* value

Unfortunately, it is difficult to adopt the desirability function as a performance measure of supply chain for two reasons. First, typical performance indicators do not have Y_{max}, Y_{min}, and T values, or the values are meaningless in many cases. Second, the desirability function cannot reflect the performance indicator criteria, which are often used in contracts with partners, the so-called SLA. For these reasons, we devise a new desirability function for the collaboration, discussed in Section 4.

3. Collaborative Performance Management

3.1 Framework

We first present a framework of collaborative performance management which is based on a methodology for collaborative performance measurement. Our conceptual framework for collaborative performance management is shown in Figure 3. We assume that partner companies who participate in the collaboration have their own environment for collaboration management such as service level management, manufacturing collaboration, performance management, and continuous improvement. Partners use collaborative performance management systems in the context of a manufacturing collaboration infrastructure described in Section 2. In many cases, such collaboration support systems may be maintained to manage collaboration process between or among the partners. In a collaboration environment, collaborative performance management has three stages: development of cKPIs, real-time collaboration process monitoring and reporting, and collaborative process performance analysis.

(1) *Development of cKPIs*: In many cases of manufacturing collaboration, the product data such as computer-aided design (CAD) files and bill of materials (BOM) documents can be exchanged among partner companies for efficient communication. Yet performance indicators and their improvement are generally managed only within individual companies for several reasons (e.g., business security, price negotiation, or accounting). To address this difficulty, we propose cKPIs for collaborative performance management. If all partners in the collaboration effectively define and measure shared cKPIs for manufacturing collaboration, they can continuously strengthen their collaboration and improve their competitiveness regarding their common goals.

(2) *Real-time collaboration monitoring and reporting*: Based on the derived cKPIs, collaboration can be evaluated in real-time and reported in order to maintain ongoing collaboration processes. Monitoring and reporting is necessary to control activities and maximize collaboration performance.

(3) *Collaborative performance analysis*: Collaborative performance analysis tools are necessary to continuously improve collaboration performance by analyzing cKPIs results and discovering how to achieve business excellence.

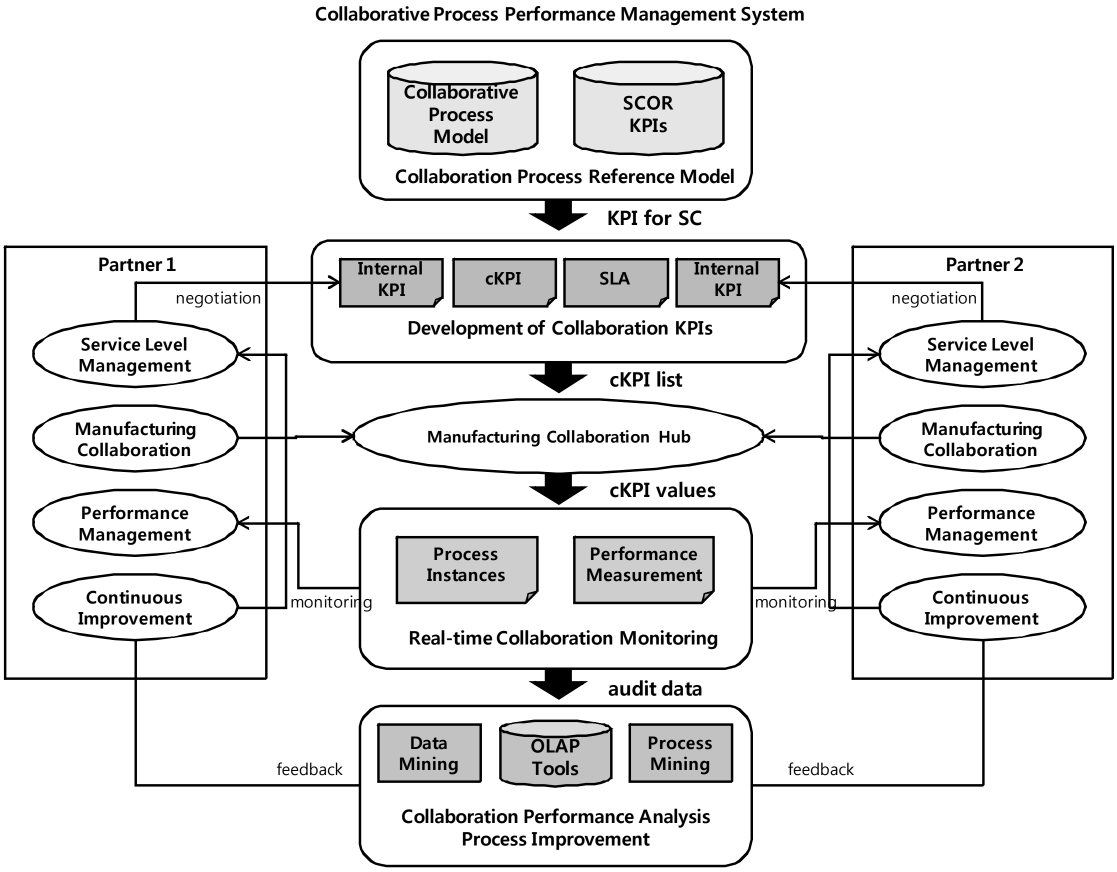


Figure 3. The framework for collaborative performance management[1]

3.2 Procedure of Collaborative Performance Measurement

In this section, we present a methodology of collaborative performance measurement for manufacturing. To define and measure collaborative performance, we use KPIs that collaboration partners can apply to measure their own business performance. In other words, collaborative key performance indicators (cKPIs) are calculated using KPIs of the collaboration partners.

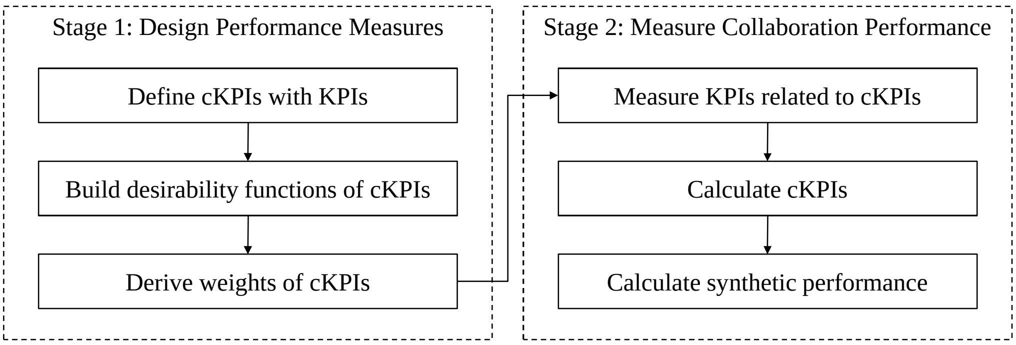


Figure 4. A procedure for collaborative performance measurement

[1] This figure is from the short version of this paper that has been presented in the 2011 International Conference on Industrial Engineering and Operations Management held in Kuala Lumpur, Malaysia during January 22-24, 2011

Published in International Journal of Industrial Engineering- Theory, Applications and Practice, Vol. 19, No. 3, Mar 2012, pp. 149-160.

The procedure of collaborative performance measurement is illustrated in Figure 4. The procedure follows two stages: designing collaborative performance measures, and measuring collaboration performance. In the first stage, several cKPIs are designed for a target collaborative process by using KPIs of individual companies who participate in the collaboration. In our research, cKPIs are defined for a collaborative process just as KPIs are defined for a business process. Then, we build a desirability function for each cKPI to transform different scales of cKPIs to values between 0 and 1. To reflect the threshold value in SLA, we develop a modified sigmoid function, described in Section 4.1. The desirability values of cKPIs, which have been transformed to the same scale between 0 and 1, are merged to calculate the synthetic performance of each collaboration case. To do that, we derive weights of cKPIs beforehand through extensive interviews with the domain experts who include the collaboration system users and managers.

In the second stage, we measure the performance indicators and calculate the synthetic performance of the collaboration on the basis of the predefined cKPIs, their desirability functions, and the weights of the cKPIs. After measuring the KPIs which are used to define the cKPIs, the cKPIs can be calculated. Finally, the synthetic performance of the collaboration case is calculated to evaluate the case and compare the performance with prior one or other partners'.

3.3 Example of Manufacturing Collaboration

To illustrate the proposed methodology, we consider an example of manufacturing collaboration process that is run in the manufacturing collaboration infrastructure in Section 2.1. It is a collaborative process for engineering design change of an automotive part. Three partners participate in this collaboration: a leading company, an automotive part supplier company, and a molding company. Figure 5 shows the BPMN model of the collaborative process between these three partners. In Sections 4 and 5, this example is also used to discuss how to apply the proposed methodology to manufacturing collaboration.

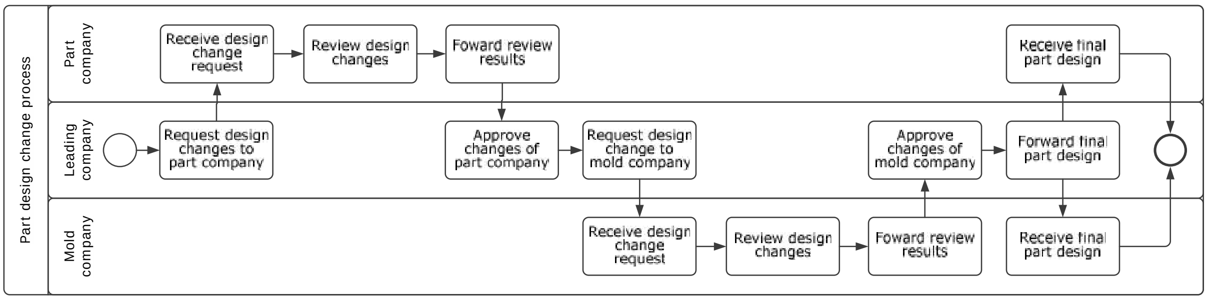


Figure 5. Example collaboration process of automotive part engineering design changes

4. Design of Collaborative Performance Measurement

4.1 Definition of cKPIs with KPIs

We first define collaborative process indicators for engineering design change process presented in Section 3.3. We adopt SCOR model, which provides a reference for supply chain processes and their corresponding metrics. The SCOR model contains five generic supply chain processes (plan, source, make, deliver, and return), along with structured performance indicators for each process. In the model, supply chain performance is measured to ensure a high level of performance indicators such as reliability, flexibility and responsiveness, cost, and asset (SCC, 2006).

SCOR model provides a hierarchical supply chain process reference model with Levels 1 to 3. In this research, we derived cKPIs of the example collaboration from the Level 2 performance indicators from SCOR model version 8, which provides 40 Level 2 performance indicators for supply chain processes. Based on these indicators, we defined four cKPIs for the example collaboration process of automotive part engineering design changes. The defined cKPI and the corresponding SCOR model are summarized in Table 1. Table 2 shows the definition of each cKPI and how to calculate the cKPIs from the value of KPIs. For instance, engineering design change cycle time for a part is calculated by summing the three partners' engineering design change cycle times, while the lost cost of the collaboration is the sum of their lost costs.

Table 1. Example cKPIs derived from metrics in the SCOR model

Process of SCOR Level 2	Metric of SCOR Level 2	Derived cKPI
ER.2. Manage performance of return processes	Manage performance of return process cycle time	Part design change cycle time
SR.3. Source return excess product	Total excess material return	Number of design change requests
R.1. Return defective product	% return	Approval rate of design change requests
DR.1. Deliver return defective product	Cost to authorize defective product return	Loss cost due to design changes

Table 2. Example cKPIs and their calculation

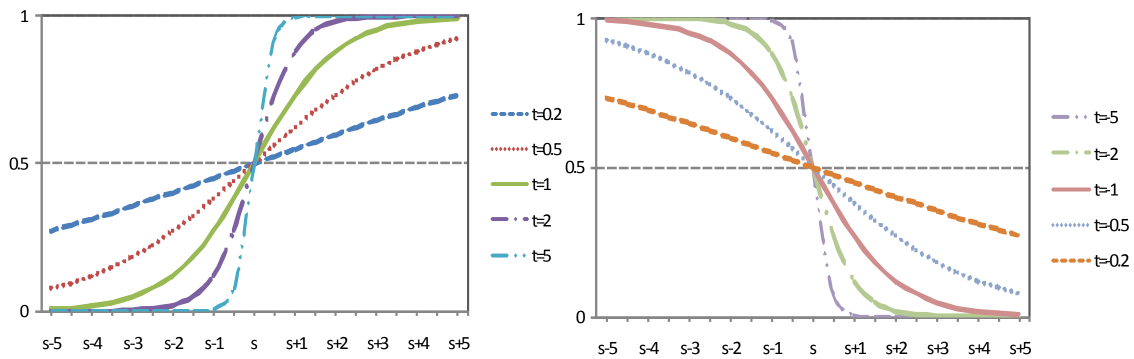
cKPI	Definition	Calculation
Part design change cycle time	Total lead time by part design change in collaboration	(design change cycle time of leading company) + (design change cycle time of part company) + (design change cycle time of mold company)
Number of design change requests	Total number of requests for design changes due to design errors or omissions	(# of design change requests due to additional requests) + (# of design change requests due to part design errors) + (# of design change requests due to mold design errors)
Approval rate of design change requests	The ratio of design change approvals to design change requests	(# of design change approvals) / (# of design change requests of part company) + (# of design change requests of mold company)}
Loss cost due to design changes	Total cost due to design changes of three partners	(loss cost due to design changes of leading company) + (loss cost due to design changes of part company) + (loss cost due to design changes of mold company)

4.2 Desirability Functions for cKPIs

In this research, desirability functions are adopted to transform cKPIs from different scales into the same scale of values between 0 and 1. Finally, the weighted desirability values of all cKPIs are summed to derive the synthetic performance of a collaboration case.

To develop the desirability functions for collaborative performance measurement, we introduce a sigmoid function based on the concept of the SLA. An SLA is often agreed upon among partners to guarantee the level of service quality. If a service provider does not satisfy the agreement, a corresponding penalty is imposed on the provider on the basis of the SLA. For that reason, a modified sigmoid function is developed to reflect the service level criteria described in the agreement. Among several existing sigmoid functions, we adopted the logistic function given in the following equation:

$$d(x) = \frac{1}{1+e^{-t(x-s)}} \tag{3}$$



(a) LTB indicators (t>0) (b) STB indicators (t<0)

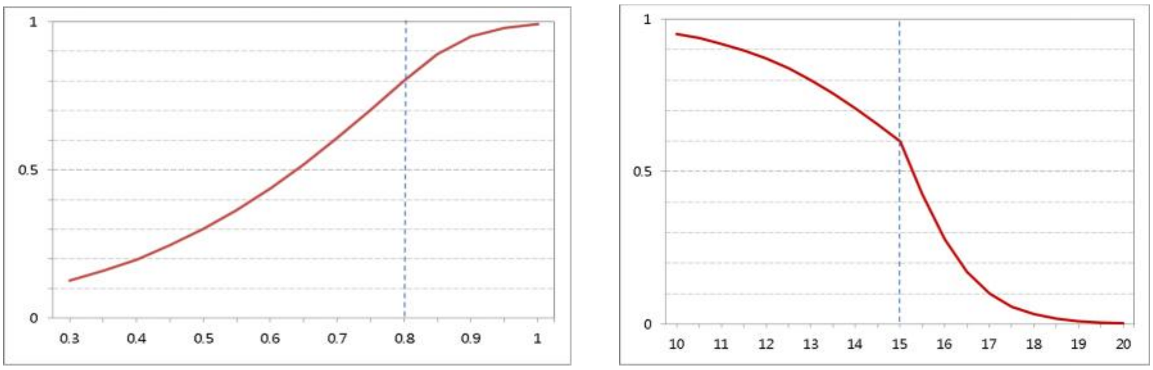
Figure 6. The shapes of sigmoid desirability functions according to *t* value

Figure 6 shows the shapes of logistic functions according to parameter *t*, and the shapes in Figure 6 (a) and (b) are for LTB (t>0) and STB (t<0) types of performance indicators, respectively. The proposed desirability function based on the sigmoid function differs from existing ones in several ways. First, we do not need to define maximum and minimum values of performance indicators in order that the sigmoid functions can output a desirability value between 0 and 1 as shown in the figures. Many performance indicators such as delivery time and production cost do not have maximum values and have negligible values. Moreover, their maximum and minimum values are too biased in practice, and therefore they are not as critical in performance management as in the machining process, for which the existing desirability functions are often applied. Second, the slope of the sigmoid function becomes steeper when the value is closer to criterion *s*. It can reflect the sensitivity around the criterion that has been agreed in a SLA. Because of these two properties of the sigmoid function, we adopt it for the desirability function of performance indicators in our research.

Table 3. Two-folded desirability functions for two types of performance indicators

Type	LTB (Larger-The-Better)	STB (Smaller-The-Better)
Equations of desirability functions	$d(x)=\frac{2h}{1+e^{-a(x-s)}}$ if $x<s$ $d(x)=h$ if $x=s$ $d(x)=\frac{2-2h}{1+e^{-b(x-s)}}-1+2h$ if $x>s$	$d(x)=\frac{2-2h}{1+e^{-a(x-s)}}-1+2h$ if $x<s$ $d(x)=h$ if $x=s$ $d(x)=\frac{2h}{1+e^{-b(x-s)}}$ if $x>s$

Moreover, we propose two-folded desirability functions as performance indicators since the slopes of desirability functions are generally required to be different between lower than and greater than criterion *s*. Table 3 summarizes the formulas of two-folded desirability functions for LTB and STB types of performance indicators according to the range based on criterion *s*. Parameter *h* is the desirability of value *x*=*s*, and parameters *a* and *b* are for the ranges lower than and greater than *s*, respectively. Two examples of two-folded desirability functions are shown in Figure 7. The first desirability function is developed for LTB cKPI 'Approval rate of design change requests', and the second for STB cKPI 'Part design change cycle time'. The parameters of the first functions are *s*=0.8, *h*=0.8, *a*=4.888, and *b*=19.459, and those of the second one are *s*=15, *h*=0.6, *a*=-0.973, and b=-1.199.



(a) Approval rate of design change requests (LTB) (*s*=0.8, *h*=0.8, *a*=4.888, and *b*=19.459)

(b) Part design change cycle time (STB) (*s*=15, *h*=0.6, *a*=-0.973, and *b*=-1.199)

Figure 7. Examples of two-folded desirability functions for cKPIs

4.3 Weights of cKPIs

In order to analyze and continuously improve collaboration performance, collaboration managers often toned to compare the performance of a collaboration case against previous periods or against collaboration with other partners. To do that, it is necessary to extract one metric for overall collaboration from many performance indicators which have been measured with individual desirability functions. This requires the weights of many performance indicators, which have to be prepared beforehand, for instance, through interviews with the domain experts.

The method of pairwise comparison can be applied among the degrees of importance of every cKPI. Suppose we have *n* cKPIs and let r_{ij} be the relative importance between the *i*-th and the *j*-th cKPIs (for $1 \le i \le n$, $1 \le j \le n$), which means that managers consider the *i*-th cKPI is r_{ij} times as important as the *j*-th one. Note that $r_{ij}=1/r_{ji}$ for every *i*, *j*, and $r_{ij}=1$ for *i*=*j*. The relative importance between two indicators can thus be reflected by the weight of performance indicator, w_k (for $1 \le k \le n$), by the following equations:

$$t_k = \sqrt[n]{r_{k1} \times r_{k2} \times \ldots \times r_{kn}} \quad (4)$$

$$w_k = t_k / (t_1 + t_2 + \ldots + t_n) \quad \text{(i.e. } \textstyle\sum_{k=1}^{n} w_k = 1) \quad (5)$$

In the example case, the three partners determine the weights of four cKPIs through the pairwise comparison of their relative importance, and the average values are used as final weights of the cKPIs, as shown in Table 4.

Table 4. Weights of cKPIs for the example collaboration

cKPI / Partner	Part design change cycle time	Numbers of design change requests	Approval rate of design change requests	Loss cost due to design changes	sum
Leading company	0.077	0.182	0.262	0.479	1.0
Part company	0.426	0.225	0.124	0.225	1.0
Mold company	0.139	0.304	0.289	0.268	1.0
weight	0.214	0.237	0.225	0.324	1.0

5. Industry Application

In this section, we describe how to apply the proposed design of collaborative performance measurement. To measure the collaboration performance of a collaboration case, the first step is to collect the KPI values that are used to calculate cKPIs. Table 5 shows the KPI values for the example of automotive part engineering design changes. The KPIs are used to calculate four cKPIs for the given example as described in Table 2. The KPIs can be LTB or STB types. For example, the number of design change approvals is LTB, while the cycle time of design change is STB.

Table 5. KPI values of the example collaboration case

Partner	KPI	Type	Value
Leading company	design change cycle time of leading company	STB	2
	# of design change requests due to additional requests	STB	5
	# of design change approvals	LTB	2
	loss cost due to design changes of leading company	STB	120
Part company	design change cycle time of part company	STB	5
	# of design change requests due to part design errors	STB	2
	# of design change requests of part company	STB	2
	loss cost due to design changes of part company	STB	260
Mold company	design change cycle time of mold company	STB	4
	# of design change requests due to mold design errors	STB	1
	# of design change requests of mold company	STB	1
	loss cost due to design changes of mold company	STB	230

Table 6 summarizes the progress of calculating the values of cKPIs and the synthetic performance of the collaboration case for the example illustrated in Figure 5. The values of cKPIs are calculated from those of KPIs in Table 4 by using the formulas given in Table 2. We assume that the parameters of two-folded desirability function of each cKPI, such as s, h, a, and b, have been obtained through interviews with experts as listed in Table 6. Then, the desirability values of cKPIs, $d(x)$, can be calculated with the equations for the desirability functions given in Table 3. For example, the value of STB cKPI 'Part design change cycle time' is the sum of design change cycle times of three companies (2, 5, and 4 days). Because the value of the cKPI, x=11, is less than criterion s=15, we have the desirability value, $d(x)$=0.919, by equation (6), which is built by applying four parameters in Table 6. In the same ways, the other cKPI and desirability values are calculated to evaluate the collaborative performance.

$$d(x) = \frac{2 - 2\times 0.6}{1 + e^{0.549(x-15)}} - 1 + 2\times 0.6 = \frac{0.8}{1 + e^{0.549(x-15)}} + 1.2 \qquad (6)$$

Table 6. cKPIs and synthetic performance of the example collaboration case

cKPI	Type	Value	Parameters of desirability function				Desirability	
		x	s	h	a	b	$d(x)$	w
Part design change cycle time	STB	11	15	0.6	-0.549	-1.199	0.919	0.214
Number of design change requests	STB	8	10	0.5	-0.277	-0.085	0.635	0.237
Approval rate of design change requests	LTB	1	0.8	0.8	4.89	19.5	0.548	0.225
Loss cost due to design changes	STB	610	800	0.5	-7.32×10^{-3}	-2.75×10^{-3}	0.801	0.324
Synthetic performance of the collaboration case							0.717	

Finally, the desirability values of cKPIs, $d(x)$, are used to obtain the synthetic performance of the collaboration case, denoted by D, by considering weights w. In this research, the synthetic performance is calculated from the weighted products of the desirability values of cKPIs, $d(x)$, using the following equation:

$$D = d(x_1)^{w_1} \times d(x_2)^{w_2} \times \cdots \times d(x_n)^{w_n} \qquad (6)$$

As a result, the synthetic performance of the given example collaboration case is calculated to be 0.717.

6. Conclusion

Existing studies on performance management mainly focus on internal tasks or on outsourcing a project from the viewpoint of a single company. Such performance measures cannot be directly utilized for collaboration processes since performance indicators often conflict between service providers and clients. As a result, we propose a methodology for measuring collaborative performance and deriving synthetic performance of collaboration cases.

In our research, we first introduce the concept of collaborative performance indicators, which are calculated from the values of performance indicators which individual partners generally measure. Then the two-folded desirability functions of cKPIs are developed to derive the synthetic performance of a collaboration processes. Finally, a method of obtaining the synthetic performance is proposed from the results of cKPIs. This proposed methodology for measuring collaborative performance and calculating the synthetic performance of a collaboration case can be used to effectively maintain and continuously improve the collaboration of multiple partners.

7. Acknowledgements

The abstracted paper this paper has been presented in the 2011 International Conference on Industrial Engineering and Operations Management held in Kuala Lumpur, Malaysia during January 22-24. This work was supported by the i-manufacturing program funded by the Ministry of Knowledge Economy (MKE, Korea) (No.B0008144-2010-06).

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