Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2016, Article ID 4049174, 11 pages
http://dx.doi.org/10.1155/2016/4049174

Research Article

Quantitative Model for Supply Chain Visibility: Process Capability Perspective

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Received 23 October 2015; Revised 19 January 2016; Accepted 24 January 2016

Academic Editor: Paulina Golinska

Currently, the intensity of enterprise competition has increased as a result of a greater diversity of customer needs as well as the persistence of a long-term recession. The results of competition are becoming severe enough to determine the survival of company. To survive global competition, each firm must focus on achieving innovation excellence and operational excellence as core competency for sustainable competitive advantage. Supply chain management is now regarded as one of the most effective innovation initiatives to achieve operational excellence, and its importance has become ever more apparent. However, few companies effectively manage their supply chains, and the greatest difficulty is in achieving supply chain visibility. Many companies still suffer from a lack of visibility, and in spite of extensive research and the availability of modern technologies, the concepts and quantification methods to increase supply chain visibility are still ambiguous. Based on the extant researches in supply chain visibility, this study proposes an extended visibility concept focusing on a process capability perspective and suggests a more quantitative model using Z score in Six Sigma methodology to evaluate and improve the level of supply chain visibility.

1. Introduction

Currently, the intensity of enterprise competition has increased resulting in severe conditions under which the survival of a company is determined. At present, companies are operating in a customer-centric environment, and the challenges they face are more difficult and broader as a result of economic globalization, greater diversity in customer needs, and shorter product life cycles that have been propelled forward by the evolution in information technology (IT). Each firm has to focus on achieving innovation excellence and operational excellence as core competency to sustain their competitive advantage and to survive in an environment with global competition. To this end, supply chain management (SCM) is regarded as the most effective innovation initiative that can be used to achieve operational excellence, and its importance has become ever more apparent. However, few companies are effectively applying SCM, and the greatest difficulty lies in achieving supply chain visibility (SCV). Many companies still suffer from a lack of visibility, and the key drivers to improve SCV have been investigated that the operational pressures of growing global operations, the subsequent increase in complexity, and the need to improve speed and accuracy are top of mind [1–3].

Recently, business competition has shifted from firm-to-firm to supply chain to supply chain competition. For the assembly industry, such as for automobiles and smartphones, the supply chain is configured in a complex manner and includes multitiered suppliers, customers, and outsourcing partners. Business performance is now determined through cooperation and collaboration of all members of a supply chain, such as with Apple and Samsung in the smartphone industry, and their competitiveness is the result of improvement through innovation excellence and operational excellence. With simple supply chain structure facilitating the outsourcing processes, Apple is executing a strategy to create predictable demand through continuous innovation in its products. Meanwhile, Samsung is focusing on achieving weekly rolling sales and operations planning (S&OP) to effectively serve customer needs while maintaining a low inventory worldwide with a high level of an SCV, and the company exploits unique innovation initiatives to synthesize SCM and

Six Sigma in order to achieve operational excellence. These two companies have been continuously identified by Gartner as supply chain leaders [4–6].

SCM can be successfully introduced by systematically implementing a strategy with the right understanding and buy-in from the chief executive officer and line managers. The first SCM strategy involves matching supply and demand. It can be achieved by operational excellence with an effective supply chain structure and a high level of responsiveness through an excellent SCV [2, 3, 7, 8]. Operational excellence is a strong competitive weapon since it is difficult to acquire. Even though many companies have tried to acquire operational excellence, there are not many successful companies that have been able to do so. This is usually a result of a poor understanding and an inadequate innovation methodology to achieve operational excellence and supply chain visibility.

The application of SCM should be designed and integrated in such a way where the information required for supply chain operations can be effectively utilized and shared. To share useful information effectively throughout the internal organizations and with external partners, system integration is necessary in order to ensure compatibility in such exchanges without distortion and disruption. However, as a result of incompatibilities of vendors, rules, processes, timeliness, and so forth, it is difficult to share the useful information externally, sometimes even internally. Despite best of breed solution, the tailoring efforts to meet local requirements and to interface with legacy systems are also not easy [2, 3, 9]. This journey requires large investments, time, and effort. From this point of view, supply chain integration has become the largest obstacle to gain SCV by information sharing.

Nevertheless, the concept of SCV in business remains ambiguous despite an extensive amount of research in the literature, and the solutions to improve business performance have not yet been determined [8, 10]. To this end, this paper suggests an extended concept of visibility and a more effective quantitative model to evaluate the level of visibility.

This paper is organized as follows. The extant literature is reviewed in Section 2. Section 3 proposes a new concept using process capability as well as the corresponding quantitative model. Section 4 shows the overall quantitative model and an example to assess visibility in the entire supply chain. Finally, Section 5 presents the conclusion for the proposed model and discusses future studies.

2. Literature Review

2.1. Definition of Supply Chain Visibility. In order to survive global competition, all enterprises and their members that belong to a supply chain must have the ability to efficiently and effectively provide goods and services to end-customers while sustaining a competitive advantage. Companies are also required to achieve operational excellence in order to efficiently and effectively deliver goods to diverse channels and to better provide value to their customers. Many studies argue that operational excellence requires a company to have sufficient information visibility to sense product movement seamlessly from end to end of the supply chain and to share timely information among supply chain partners. These days, the importance of SCV has gradually increased, and research on this topic is varied and extensive. Thus, this study first presents a review of extant researches from various perspectives based on that previously provided by Caridi et al. [10].

The majority of participants in US manufacturing have reported that having disparate systems makes it difficult to coordinate with partners, and differences by vendors and a lack of compatibility of the SCM applications that are used prevent access to valuable external data. This lack of data access results in a lack of visibility into the supply chain [7]. The Aberdeen Group conducted a survey and found that the majority of participants identified an improvement in operational performance as the main value of SCV, and they have undertaken initiatives to improve visibility or plan to do so in the future. They also suggested that end-to-end SCV plays a critical role in SCM by contributing to creating more controllable, responsive, and financially healthy supply chain [11].

Zhang et al. described the three stages of inventory visibility (IV): shipment tracking, supply chain events and disruption management, and continuous improvement in the supply chain. They posited that IV provides a means to track goods and materials, a better decision making in disruptive events management, and a measure for a key indicator for supply chain performance improvement [12]. Barratt et al. presented that a concept of visibility has sometimes been used with information sharing within the extant research, but information sharing is an activity and visibility is a potential outcome of such activity, and this potential visibility may lead to a more effective supply chain. They defined SCV as "the extent to which actors within a supply chain have access to or share information which they consider as key or useful to their operations" [13, 14]. Holcomb et al. described that the growing importance of visibility to enable greater efficiency and effectiveness has propelled firms to invest in improving these capabilities. They posited that the way to achieve the dual objectives of efficiency and effectiveness is through end-to-end seamless SCV [7]. Goh et al. proposed that SCV is related to collaborative decision making between supply chain partners and that it provides a means to support decision making from tactical and strategic perspectives [15]. Caridi et al. described SCV as the ability of a supply chain leader to access/share information related to strategy and operations of their supply chain partners. They evaluated that although SCV is commonly discussed in the SCM community, its meaning is still somewhat ambiguous [8, 10].

2.2. Quantification of Supply Chain Visibility. As described above, numerous studies have been conducted to define SCV and to present a quantified model. Typical methods involve grading system obtained through surveys or case studies, and others involve mathematical techniques to handle the quantity and quality of information utilized among supply chain members [10, 12, 13, 16–18]. Most of the extant research belongs to the former, and seldom to the latter, but we introduce two cases of the latter.

Caridi et al. suggested that visibility can be defined in terms of access to useful information, and they proposed a quantitative model to measure visibility for supply chains longer than two tiers. SCV is measured according to the amount and quality of useful information when compared to the total information that could be exchanged between nodes in a supply chain. The four different types of information flows that are considered are transactions, status information, master data, and operation plan. They tried to quantify the data with a semiquantitative judgement for quantity, freshness, and accuracy using an analytic hierarchical process methodology based on the experience of supply chain managers [10, 16–18]. Zhang et al. posited that IV is a capability of a supply chain actor to have access to or to provide timely information of the inventory involved in the supply chain from/to the relevant supply chain partners to support better decision making. They suggested two types of capabilities to access the information that is available and to provide information available in the supply chain. They tried to quantify the information using a model for the relations among the information items and the supply chain partners [12]. In both cases, they tried to make a more objective quantification making use of the information for the SCV.

2.3. Business Performance and Its Measures for Supply Chain Visibility. This paper explored current studies relating business performance to SCV, operational excellence, and process capability field to understand the effect of supply chain visibility and its measures.

Regarding SCV, Wei et al. posited that SCV is an important factor that enables supply chain reconfigurability, which is an important dynamic capability for supply chains from the point of view of dynamic capabilities, and SCV has a strong influence on supply chain performance through supply chain reconfigurability [19–21]. Caridi et al. defined the level of visibility with data readiness and data usability and shareability by obtaining data generated from activity in the actual supply chain. They proposed a value assessment method to improve business performance by using cause and effect mapping linked with activity data in the form of a business key performance index (KPI) [10, 16–18, 22]. Li et al. addressed the bullwhip effect in a control problem in the context of a supply chain system facing uncertainty. They used endogenous SC dynamics to build a supply chain state transition model and focused on the effect that uncertain order placement lead time delays had on replenishment [23, 24]. Gaukler et al. studied how order progress information can be used to improve inventory replenishment decisions and numerically evaluated the cost savings of stochastic lead time and demand variability in the order fulfillment [25]. Chew et al. investigated the impact of SCV on inventory management by studying how inventory decisions and costs are affected by the ability to track orders as they flow from suppliers to retailers, passing through various intermediary locations. They modeled the effect of lead time through changes in the lead time density distribution function [26]. Goel showed how in-transit visibility can be used to adjust the transportation plan with respect to the known state of a transportation system facing variability in transportation times, and on-time delivery performance can be significantly improved by increasing the level of visibility [27]. These studies similarly evaluated the cost and delivery performance corresponding to the change in the lead time according to visibility grade by controlling the delivery route.

Regarding operational excellence and process capability, several researchers have studied the effect that delivery lead time has on business performance. Kane proposed capability indices to effectively summarize process information, process potential, and performance information [28]. Tanai and Guiffrida studied lead time compression and variability reduction, process capability indices, and the Six Sigma program. They proposed a delivery performance model in terms of both the mean and variance of the delivery time distribution by considering the delivery window [29]. Garg et al. focused on reducing the variability and synchronizing business process to achieve timely deliveries throughout the supply chain, and they developed a heuristic approach using process capability indices to solve supplier selection problems [30]. Wang and Du proposed a capability index that establishes a relationship between customer specification and the actual process performance by solving the supplier selection problem [31]. Guiffrida and Jaber addressed the managerial and economic impact of improvements in delivery performance by conducting an evaluation with a delivery window, and they modeled the variance of the delivery time as a function of the investment in order to reduce the delivery variance and the costs associated with an untimely delivery [32]. Narahari et al. studied a Six Sigma approach to analyze a process through which Six Sigma performance is delivered in order to design synchronized supply chains with that focus on process capability indices [33]. Dasgupta suggested a framework to effectively measure and monitor supply chain performance focused on rolled throughput yield (RTY) and delivery performance using Six Sigma metrics as Z-value [34].

In summary, most studies have used the variation in the delivery lead time to evaluate the business performance according to the costs that correspond with a timely delivery. In order to calculate the costs, the distribution of the delivery time has used itself or the process capability using a delivery window. The former shows that the improvement in visibility increases business performance by enhancing the distribution of the delivery time. The latter shows that the delivery time distribution can be represented by a process capability and that business performance can be evaluated by costs as well as the process capability index.

2.4. Gap in the Extant Researches. In this study, we reviewed the definition and quantification methods that were suggested in various aspects. Most research has the general consensus that SCV can have a profound impact on businesses performance. However, the manner in which visibility can be defined and quantified has not yet been fully developed. Nevertheless, researchers have expanded extensive efforts in developing the concepts for SCV and have further established its importance.

However, Caridi et al.'s analysis describes how despite a large number of articles being published research on the benefits of visibility still remains mainly theoretical, and the main performance indicators that are affected by improvements in visibility have yet to be identified since most studies focus on only one or on a subset of the impacted indicators.

It also describes how most papers are limited in their capacity to analyze the dyadic relationship between retailers and manufacturers except suppliers, to explore the benefits on downstream players, and to consider information flows relating sales and demand forecasting. Caridi et al. have also evaluated how existing models provide an incomplete evaluation of the benefits enabled by visibility [10]. In addition, most of the extant research is limited to the study of the delivery time or RTY to evaluate business performance. In practice, various performance factors are managed for a supply chain to meet business goals as itself or as a component of KPI, such as with lead time, yield, quality, utilization, inventory, costs, and sales. Thus, it is necessary to expand research to consider more factors.

3. Quantification Model of Supply Chain Visibility Using Process Capability

In the previous section, this paper presented a review of numerous studies with various perspectives and definitions of SCV, and the importance and role of SCV were also investigated. Most of the extant research can be classified into two groups. The first group proposes SCV for information management and sharing from IT perspective, and a quantified model is suggested according to the quantity of information. The second group proposes SCV from resource-based theory perspective. The latter posited that SCV is an outcome of information sharing and that it leads to an improvement in operational performance for SCM. This paper thus described the concept of SCV from a more practical point of view, and it proposes an extended concept from a perspective of process capability and a more practical and objective quantification model based on this concept.

3.1. Critical Factors Inhibiting Supply Chain Performance. The core value of SCM is to efficiently and effectively exploit the key factors over the entire supply chain, and this achieves profit maximization and sustainable growth, which are the most important targets for enterprises. To this end, a responsiveness corresponding to variability and uncertainty throughout the entire supply chain, like bullwhip effects and risks, must also be improved. Also, the deployment of win-win structure based on a true partnership is important in order to share the supply chain status and performance and to collaborate and cooperate among supply chain members as suppliers, customers, subcontractors, and logistic service providers. To improve responsiveness, operational excellence must be achieved to effectively conduct a supply chain plan. This is realized by undertaking process innovation initiatives and process robustness throughout the entire supply chain.

Various factors affect the supply chain process, and those are buried and unseen in the process, as mentioned in Feigenbaum's "hidden plant." Supply chain performance greatly depends on governing for critical factors as a common cause or as a special cause of process disability. The critical factors that inhibit performance in a supply chain can be classified as planning factor and operational factor. The planning factors can be divided into a demand factor from the downstream direction and a safety factor for internal processes. In addition, the operational factors can be divided into an endogenous factor and an exogenous factor.

With respect to planning factors, demand factors are mainly generated by demand processes, and this typically leads to a bullwhip effect, as described in Forrester's Industrial Dynamics [35] and suggested by Lee [36, 37]. Safety factors are a result of the level of process maturity represented as process performance metrics. The level of process maturity affects the process schedule as a safety buffer that is added to the planning parameters upstream as a feedback loop in the system dynamics. The buffer is determined by the planner's experience and its effect is also amplified toward the upstream across the supply chain. If the process is more unstable, the buffer is greater. Moreover, the planning factors increase the information variation upstream.

Endogenous factors to a supply chain system are generated by various causes including machine breakdown, poor materials, poor process control, work accidents, and rework, as shown in Figure 1. The results are manifested as long lead time, poor yield, poor quality, inventory levels with a high variability, and so on. These are quantifiable using their mean and variance as process performance metrics of a supply chain. Exogenous factors also include the variations from upstream processes when the supply chain is executed. This is combined with an inherent variation in the process by endogenous factors, and the process variation is amplified in the downstream direction during the execution of the supply chain. The upstream variation is carried over into the downstream as a domino effect, and the entire process maturity is degraded to the lowest one across the entire supply chain.

This phenomenon is more complex in a typical manufacturing supply chain composed of multiproduct, multiechelon, and multichannel suppliers and customers. As a result of these impediments, a discrepancy occurs between planning and execution. Since this process is not well executed as planned, a vicious cycle of mutual distrust is repeated between organizations that plan and those that execute. The best remedy to solve these problems is to improve process capability. It is possible through an operational excellence basically through various innovation initiatives by minimizing the variability due to demand, visualizing the behavior resulting from critical factors, mitigating uncertainty and variability, and improving critical factors throughout the entire supply chain. In addition, an information management ability is required that information on the status of a vital cause and behavior can be accurately sensed and visualized using various technologies, and the required information can flow seamlessly from one end to the other end of the supply chain, and the usable information can be shared in a timely manner among the supply chain partners.

3.2. Concept of Supply Chain Visibility Based on Process Capability. In business operations, invisible states occur as follows: a company's process in a black-box state, a state where it is not possible to predict the outcome of the process, a state without exchange or sharing of information among stakeholders or partners, a state where various interpretations can be made from a shared meaning, a state that varies depending on people such as managers or executives, and

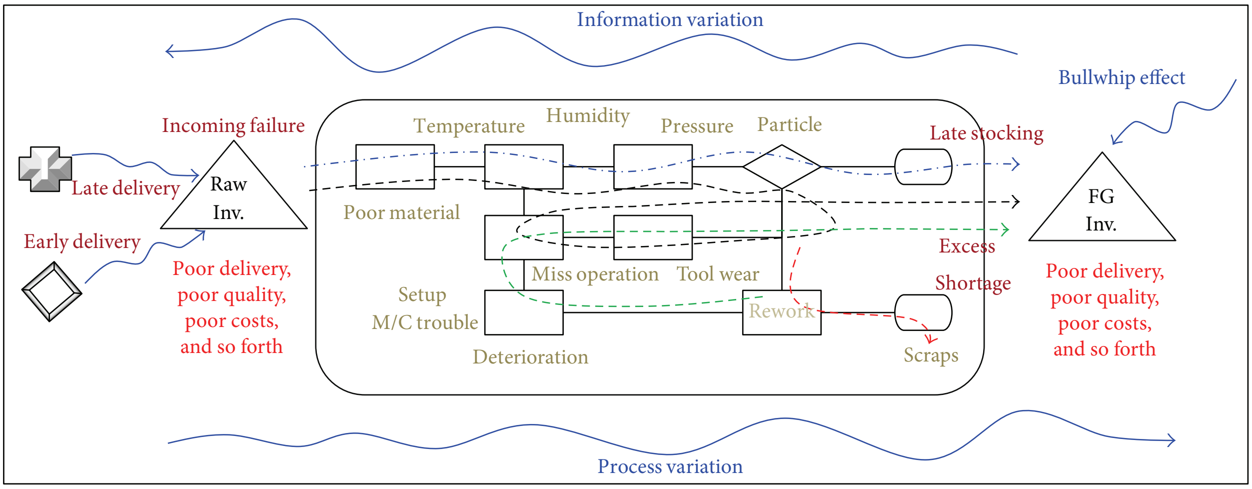

Figure 1: The critical factors inhibiting supply chain management.

a state without information that can be used to evaluate decision making or business performance. SCV plays several key roles in SCM. The first role is to provide information on the status for key factors that exist across supply chain processes, such as in 5M1E (man, machine, material, method, measure, and environments). The second is used as the master data for supply chain planning and operations. The third is to represent the impact of uncertainty and variability due to the impediment of hidden factors in the business processes. The fourth is to share the current ability level to conduct supply chain operations and decision making with supply chain members. SCV should present the status and ability level for key factors in the supply chain as well as a predictable level for viable degree of supply chain plan. It is similar to the visibility to drive an automobile safely to its destination by clearly discerning the visible distance at which an object or light can be seen. In the respect, this study proposes the extended concept for SCV as the following clauses. Differently with information visibility focused on information processing, it is classified as "process visibility" that focuses on a perspective of operational capabilities. This paper suggests that SCV is

(1) visible level which manifests the status and behaviors of various factors in the supply chain,

(2) the ability for sensing and sharing variability in the supply chain process,

(3) the process maturity achieved by improvement initiatives for the key factors of the supply chain,

(4) predictable level for the viable degree of supply chain plan and outcome of process's activity.

Most of the previous studies have proposed an information visibility perspective where SCV depends on information sensing, information sharing, and maintaining the quality of information regarding supply chain factors. However, this study approaches the visibility of processes in terms of the capability of the supply chain to execute the supply chain plan. This research proposes that SCV is the degree to which the adherence to the supply chain plan can be predicted. SCV indicates the viability to execute the supply chain plan according to process capability. A lower process capability may lead to a higher probability where the business goals cannot be met due to a lack of operational capability to execute the supply chain plan. Even though the processes have the same lead time, it can predict that a process with a lower variance is executed with a higher level as planned.

Process capability can be improved by reconfiguring and transforming processes and key factors, which have to be highly visible, and the processes should be suited to achieving business goals by undertaking innovation initiatives. Also, operations and key factors for the target process should be well defined and cured for vital causes to achieve a higher process capability and robustness. SCV is an outcome that has formed through these initiatives and the process maturity level to realize the status and behavior of the process. When a process owner can predict and control the output of the process corresponding to their business strategy, then the owner can be said to have a high level of SCV based on operational excellence. Also, if the process has a higher visibility, the viable degree of the supply chain plan might be more predictable.

3.3. Quantification Model of Supply Chain Visibility Using Process Capability. The quantification for SCV is required for various purposes. Many researchers have tried to quantify an SCV using various models. However, most studies have focused on information management viewpoint as an information sensing using a barcode, radio frequency identification devices, and sensors; an information sharing between partners and an interorganizational system integration; and an information visualization using various graphical tools or dashboards. Some research has been attempted to quantify visibility by measuring the quantity and quality of information that is shared between the supply chain partners. This viewpoint evaluates the visibility according to the information maturity level rather than the operational ability of the supply chain process. However, from a process capability perspective, this paper suggests that it is more important to have an operational ability of real processes to produce and deliver rather than an information maturity throughout the supply chain. Accordingly, this research devises a methodology for quantifying mutually sharable and easily measureable the operational ability of a process. This paper thus established that the process visibility metric has to satisfy the following requisites:

(1) Single value with a unique meaning in the supply chain.

(2) Common usable value that can assess the SCM's core value and be used for benchmarking.

(3) Quantifiable value to reveal the operational status and behaviors of the process.

(4) Statistical value that can represent the process capability.

(5) Value that reflects the variability from both upstream and downstream.

(6) Predictive value of the outcome for the supply chain plan.

Requisite (1) means that the value must be something that all supply chain members can equally understand and recognize in terms of concept, meaning, and quantifying method. If the degree of understanding for the same element is different from others, the value is not appropriate for SCM. Requisite (2) means that the quantified value must be commonly useable regardless of the measured time and the measurers of a mutual comparison and trend control. Requisites (3) and (4) represent how the value must be a thing that can be numerically and statistically measured regarding the operational status, ability, and performance of the process. Requisite (5) defines how the value has to reflect the variance that has propagated both upstream and downstream, such as the information and process variation discussed in Section 3.1. Requisite (6) describes what the value can do to represent and predict the outcome of the operation when executing the supply chain plan.

To effectively execute a supply chain strategy and plan, various innovation initiatives and activities need to be executed. The results of the activities represent the various operation performance factors, such as the process lead time, yield, quality, utilization, lateness, and shortage for each of the supply chain processes. In the field, these are managed as a KPI itself or as a key factor. These are also used as master data for supply chain planning, time series analysis, and competitive benchmarking. However, since the mean of performance factor is mostly used as a measure, the uncertainty, variability, and process capability in the business process are not properly reflected. By these results, the predictability of the supply chain plan is limited. Hence, requisites (5) and (6) are very important conditions that are necessary for this research.

Although an individual KPI is used as an index to evaluate the unit process ability, the influence of the changes in the process might be represented as a trade-off with other indices. For example, if the final quality inspection to improve the quality of the finished goods is strengthened by increasing the sample size and the total inspection and reinspection, the quality of the final product may have also substantially increased. However, the overall process lead time and costs might have excessively increased. Also, if the batch size to improve the process lead time is excessively reduced, the productivity might also have greatly deteriorated. When operating a process, it is difficult to properly evaluate the performance of the entire business process with some indicators. From this perspective, this paper defines that the entire business performance $P(\cdot)$ is a result of multiplying the individual performance indices; that is, $P(\cdot) = \prod_i f_i(\cdot)$ (where f is performance factor and i is the number of performance factors). The idea to calculate the entire business performance is derived from the formula to calculate a RTY by Graves [38] and Dasgupta's framework to evaluate performance using a RTY concept [34]. Based on this idea, this study has devised a visibility equation to consider the trade-offs among the performance factors and to calculate the overall visibility. For this purpose, it needs a composite measure to reflect the key performance factors for the entire business process. In the supply chain, it is used for various measures to assess process capability corresponding to business performance. The measures are mean, median, mode, variance, standard-deviation, range, covariance, and so on. In statistical process control, it is used with C_p in (1) for the short-term process capability and with C_{pk} in (2) to consider the biased process mean indices for the lower specification limit (LSL) and upper specification limit (USL). Also, Z_{bench} in (3) is used to evaluate the process capability at Sigma level with a Z score in Six Sigma methodology. The short-term process capability Z_{st}, which is referred to as the Sigma level ($=Z_{\text{bench}} + 1.5$), shifted by 1.5σ:

$$C_p = \frac{(\text{USL} - \text{LSL})}{6\sigma}, \quad (1)$$

$$C_{pk} = \min\left(\frac{(\overline{x} - \text{LSL})}{3\sigma}, \frac{(\text{USL} - \overline{x})}{3\sigma}\right), \quad (2)$$

$$Z_{\text{bench}} = \min\left(\frac{(\overline{x} - \text{LSL})}{\sigma}, \frac{(\text{USL} - \overline{x})}{\sigma}\right). \quad (3)$$

The Six Sigma approach is one of the most widely known best practices. Six Sigma metrics have the primary advantage of being able to compute the performance of any process on the same scale and benchmark it against world-class performance [31]. To this end, the process capability indices that utilize statistical process control are the best measure on the purpose of this research. Furthermore, we determined for Z score in Six Sigma to be the most effective for this research in several process capability indices because a supply chain is configured with various types of processes, such as manufacturing, ordering, procuring, and delivering process and Six Sigma methodology has already been verified for all types of business processes. Thus, this research has devised a mathematical model to quantify the process visibility using Z score as a process capability. Z_α value is defined in (5), where $f(x)$ denotes the pdf of the standard normal distribution. We defined the visibility index of a process i (v_i) by using

TABLE 1: Example of process visibility for lead time.

Process	$\overline{x}$ (day)	σ (day)	LSL (day)	USL (day)	C_{pk}	Z_{bench}	Z_{st}	v
A	6.0	0.5	—	7.0	0.67	2.0	3.50	0.58
B	6.0	0.33	—	7.0	1.00	3.0	4.50	0.75
C	5.0	0.5	—	7.0	1.33	4.0	5.50	0.92
D	5.0	0.5	—	6.0	0.67	2.0	3.50	0.58

the process capability (Z_{bench}) in Six Sigma methodology as follows:

$$v_i = \min\left(\frac{(Z_{\text{bench}} + 1.5)}{6}, 1\right), \quad \text{where } 0 \le v_i \le 1.0, \tag{4}$$

$$\int_{-\infty}^{z_\alpha} f(x)\, dx = \alpha. \tag{5}$$

In this paper, we propose a visibility index for a business process by using the process capability, as defined in (4), which measures the operational capability of a process with its mean and variance in traditional quality control theory. The rationale is as follows: if the process capability is larger for a particular process, then the process is more likely to be stable with a smaller variation, and the outcome of the process is more likely to be excellent. On the other hand, if the process capability is smaller, then the process is out of control with greater variation because some vital cause factors are not sensed and not cured, which will make it difficult to predict the outcome of the business process with accuracy.

This method can evaluate the internal ability, control the responsiveness for customer requirement, and benchmark competitors using the specification limits. To consider multiple performance factors in the supply chain, we have configured visibility indices that are bounded by a real value between zero and one, as in (4). Under these conditions, the visibility indices can be manipulated with mathematical operations, such as multiplication and division. In the individual echelon of a supply chain, the process capability is a multiplexed outcome of various performance factors, and it tends to deteriorate according to the weakest factor. This model can thus be used to quantify the SCV more objectively and more empirically than with existing visibility models.

3.4. Numerical Example. Table 1 shows the process visibility value v that was calculated by using the mean ($\overline{x}$), standard deviation (σ), and specification limits (LSL, USL). Process A has 6 days for the mean, 0.5 days for the standard deviation, and 7.0 days for USL while LSL is not restricted. For example, the values can be as follows: C_{pk} is 0.67 [$= (7-6)/(3*0.5)$], Z_{bench} is 2.0 [$= (7.0-6.0)/0.5$ or $3*0.67$], Z_{st} is 3.5 ($= 2.0+1.5$), and the visibility v is 0.58 [$= \min(3.5/6, 1)$]. Process B changes the standard deviation from 0.5 to 0.33 days, and the other conditions are the same with process A. According to the difference of σ, process capability is much larger than process A. Process C is different from the mean of A, and according to the difference in $\overline{x}$, the visibility for C (0.92) is the largest when compared to processes A (0.58) and B (0.75).

TABLE 2: Values for the variation by variable.

Change (%)	X	Δv	σ	Δv	USL	Δv
−50	1.0000	0.0000	0.9167	0.1111	0.2500	0.0000
−40	1.0000	0.0167	0.8056	0.0794	0.2500	0.0000
−30	0.9833	0.1333	0.7262	0.0595	0.2500	0.0000
−20	0.8500	0.1333	0.6667	0.0463	0.2500	0.1667
−10	0.7167	0.1333	0.6204	0.0370	0.4167	0.1667
0	0.5833	0.1333	0.5833	0.0303	0.5833	0.1667
10	0.4500	0.1333	0.5530	0.0253	0.7500	0.1667
20	0.3167	0.0667	0.5278	0.0214	0.9167	0.0833
30	0.2500	0.0000	0.5064	0.0183	1.0000	0.0000
40	0.2500	0.0000	0.4881	0.0159	1.0000	0.0000
50	0.2500	0.0000	0.4722	0.0159	1.0000	0.0000

This shows that the improvement in the mean is more valuable than the improvement in the variance under the same specification limit. In addition, if the specification limit for USL is tighter to 6.0 days, as follows from process D, the process visibility drastically deteriorates to 0.58. Even though the current visibility is larger due to the good process capability, it loses the competitive advantage if the customer requirements or the competitor's capability is beyond what is achieved at the current level. Therefore, continuous improvement is required to maintain a sustainable competitive advantage.

3.5. Sensitivity Analysis. The proposed visibility model uses the mean, standard deviation, and specification limits to calculate the visibility level for the various performance indices. The specification limits may be the customer's requirements or the firm's strategic target value for sustainable competitive advantage. The mean and standard deviation are the outcomes of the process by executing the supply chain plan. This section thus examines the suitability of the proposed visibility model according to the sensitivity analysis.

In general, there are various performance factors in the supply chain, but this research has selected the delivery lead time that is the most representative performance index used to evaluate OTD. To conduct a sensitivity analysis, it is rewritten to $v = \min((\text{USL} - \overline{x})/(6\sigma) + (1/4), 1)$ in formula (4). It is assumed that the process for Z_{bench} is 2.0 with OTD = 97.7%, and the change of v is analyzed for each input variable that increases with a rate of 10%. To do that, the base point $(\overline{x}, \sigma, \text{USL})$ is set to be equal to (8.0, 1.0, 10). Table 2 shows the output variable v changing from the min to the max value in increments of 10% of its value for the input parameters. Figure 2 shows the results in a spider plot. For the mean, v is the inverse correlated to the mean and decreases by 0.1333

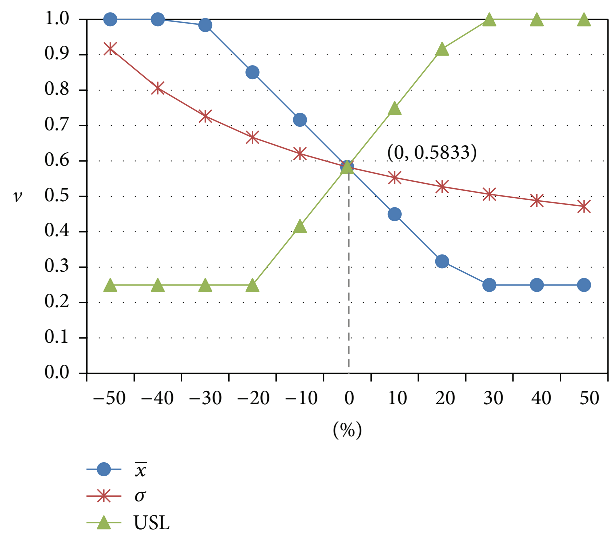

Figure 2: Spider plot for sensitivity analysis.

in 10% increments of the mean ($\Delta v = 0.1333$ at ±10%). For USL, v is the positive correlated to USL and decreases by 0.1667 with a decrease of 10% of USL. This means that USL is more sensitive than the mean. For the standard deviation σ, v decreases slightly changing into a concave shape to the right from the left. The results indicate that if the mean of the lead time is reduced, the visibility v becomes greater. However, if the USL is tighter to decrease according to customer requirements or the competency strategy, the visibility v greatly decreases in proportion. Prior to the changes in the USL due to customer requirements or competitor's competitiveness for lead time, it is necessary to improve the process capability in order to secure a competitive advantage. This result of the sensitivity analysis allows for the proposed model to be well aligned with the corresponding changes in the input variables to sufficiently reflect the process capability to respond to the company's process changes.

4. Assessment of Overall Supply Chain Visibility

4.1. Quantification Model for the Overall Supply Chain Visibility. In Section 3.3, this paper proposed a quantifying method using a Z score in Six Sigma to calculate the process capability by measuring the mean and the standard deviation of a process for the individual performance indices. The method that is used to calculate the individual index allows the visibility to be quantified by unit processes in each stage of the supply chain. This can also be expanded to calculate the overall visibility for the entire supply chain. Therefore, these results can be compared with the other stages in the same supply chain. Furthermore, by looking at the vital factor that has the lowest value, the performance of the bottleneck operation for a given stage can be improved, and the overall SC visibility can also more easily improve. For this, this paper proposes a quantification method for the overall supply chain visibility as follows. The supply chain network structure is configured as in Figure 3 based on the suggested model by Lambert et al. [39].

Step 1. Define the stages and process units in the supply chain: s—stages, u—process units.

Step 2. Define the major performance indices f and their parameters: f—factors.

Step 3. Calculate visibility instances by factor for item i at process unit u in each stage s: v_{suif}.

Step 4. Calculate the item visibility for process unit u in stage s: $v_{sui} = \sqrt[f]{\prod_f v_{suif}}$.

Step 5. Calculate the unit visibility by process unit u for each stage s: $v_{su} = \sum_i k_i \cdot v_{sui}$, where k_i is weight of sales revenue for item i, $0 < k_i \leq 1.0$, $\sum_i k_i = 1$.

Step 6. If a process unit has multiple substages or multiple subprocess units, calculate the visibility using geometric mean for their subprocess units.

Finally, calculate overall visibility: $v_{\text{overall}} = \sqrt[nsu]{\prod_{su} v_{su}} = \sqrt[nsu]{\prod_{su} \sum_i (k_i \cdot \sqrt[f]{\prod_f v_{sif}})}$, where nsu is the number of process units for overall supply chain.

Step 1 defines the stages s and process units u in the supply chain as manufacturing, inbound and outbound logistics, supply, demand, and outsourcing process. Step 2 defines the major performance indices f for process visibility at each stage s and defines the parameters (average, standard deviation, and USL or LSL as target) in order to calculate the process capability for stage s and the performance index f. For the major performance indices, the examples include the process yield, manufacturing lead time, utilization, quality, delivery lead time, and shortage performance. In the logistics processes, the delivery lead time is the key factor, and its target value may be defined by the customer or by the lead time strategy when considering the competitive advantage. Step 3 calculates the instance of the visibility of index f for each item i for process unit u at stage s: v_{suif} using the parameters in Step 2. Step 4 calculates the visibility of item i for process unit u at stage s, and the results can be compared to those of other products. Step 5 calculates the process unit visibility by weighting and summing the item visibility considering the sales revenue of the item. The unit visibility value can be compared to other stages in the current supply chain or to other competitors for the similar business processes. Finally, Step 6 calculates the overall visibility that is powered in each stage's values for all stages of the current supply chain network. This result is thus used to obtain the overall process visibility for the entire supply chain, and it can also be used for comparison with competitor's values.

4.2. Example of the Overall Supply Chain Visibility. As shown in Figure 4, this paper presents an example that can be used to more easily understand and calculate the overall

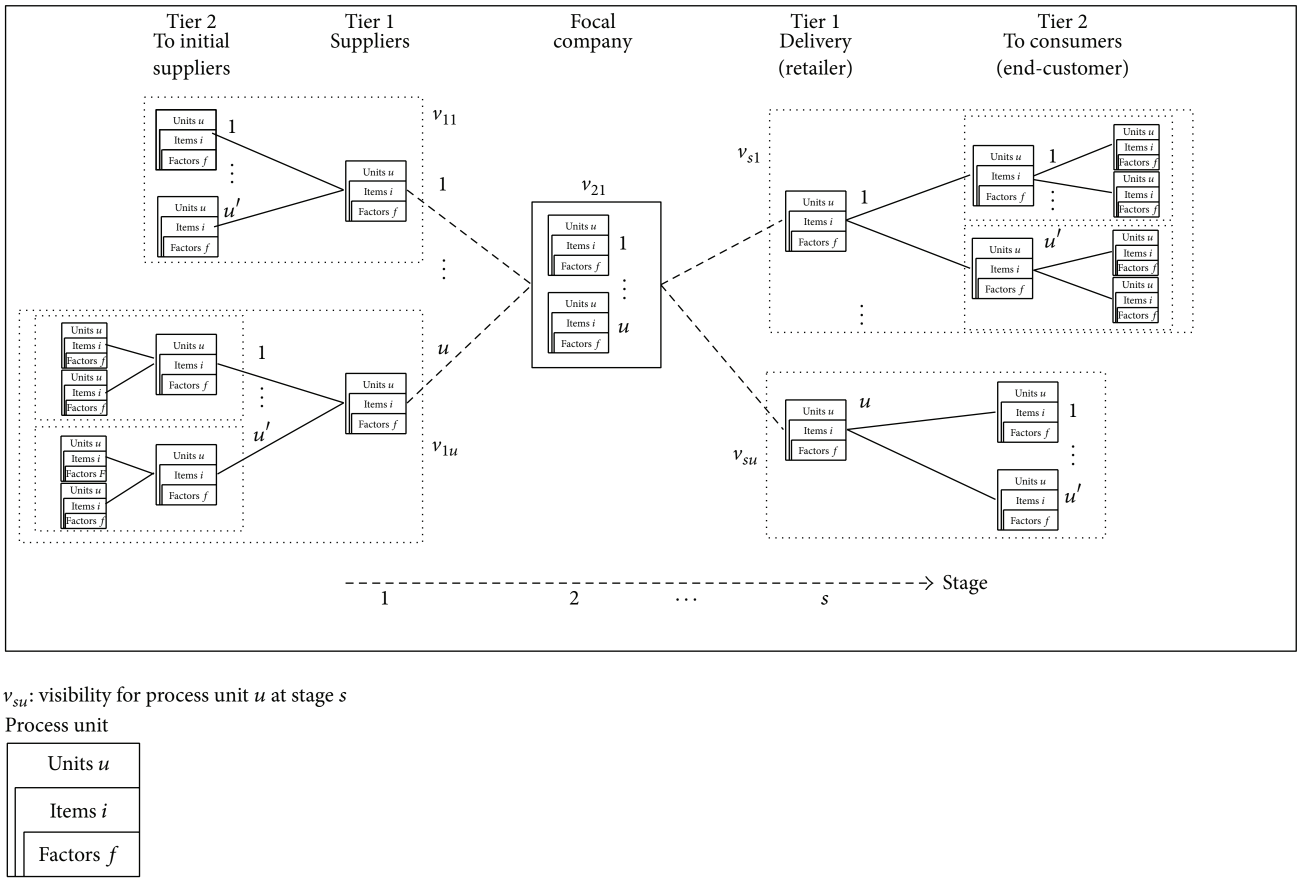

Figure 3: Supply chain network structure for visibility assessment.

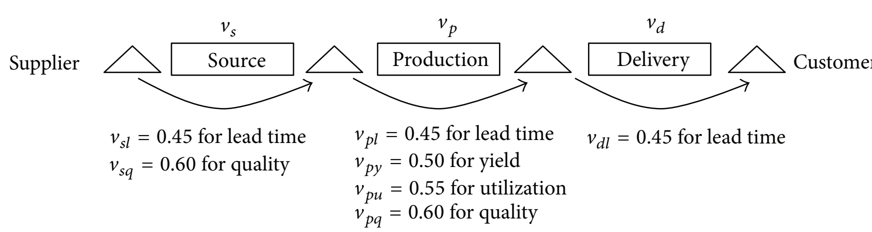

Figure 4: Example of the overall supply chain visibility.

visibility index. This supply chain is a case that produces and delivers a single product composed of 3 stages, including the *source* stage, which is the procurement process to purchase materials from supplier; the *production* stage, which consists of manufacturing to make a product; and a *delivery* stage, to transport finished goods to the customer. In the example, this paper described only the result from the v_{stage} for the stage visibility for convenience by calculating the equation in Step 4 of the previous section. If the lead time of the *delivery* stage is of about 88.5% ($z = 1.2$), v_{sl} is calculated as $\min(((1.2 + 1.5)/6), 1) = 0.45$.

For the source stage, where the visibility instances are, respectively, 0.45 for lead time and 0.60 for the quality, the stage visibility v_s is 0.519 ($= \sqrt{0.45 * 0.6}$). For the production stage, where the visibility instances for the process yield and the utilization have been added, the result v_p is 0.525 ($= \sqrt[4]{0.45 * 0.5 * 0.55 * 0.6}$), multiplied by each visibility instance. In the production stage, the stage visibility deteriorates more than the source stage due to the visibility of the yield and utilization. According to this result, it can estimate that the production process may become unstable due to the yield and utilization. For the delivery stage, where the visibility instance is only one factor for the lead time, the stage visibility v_d becomes simply 0.45. Finally, the overall visibility v_{overall} is 0.50 ($= \sqrt[3]{0.519 * 0.525 * 0.45}$), followed by Step 6 in the previous equation. This v_{overall} is reduced to 0.5 by the delivery stage visibility v_d, which is lower than that at the source stage and the production stage. It can estimate the Six Sigma level to be about 3.0 ($= 0.5 * 6$), and the process capability is 1.5 ($= 3.0 - 1.5$) with a low grade. Hence, the overall visibility can increase by initiatives to improve the entire supply chain because the visibilities for all stages are at a low level.

Since this example considers a single product with its visibility indices, the performance index that needs to be improved can be primarily decided through intuition. However, in a real supply chain, it is impossible to easily and intuitively make a judgment because the supply chain is a very complicated system that is composed of multiple products, multiple stages, and multiple suppliers and customers. Therefore, through a more objective and more quantitative approach as the proposed model, the SCV can evaluate more effectively, compare it to that of other supply chains or competitors, and analyze trends.

5. Conclusion and Further Research

This paper has proposed a quantitative approach that is more practical and objective than that of previous studies regarding SCV. Most of the extant literature has proposed using an information visibility model that focuses on usability, shareability, and integrity among partners in a supply chain from an information management perspective. These studies have mainly presented quantitative methods based on the data readiness, such as quantity, accuracy, and freshness, with an emphasis on utilizing information technology. From a conventional point of view, a reactive approach that focuses on information visibility is very important, but a proactive approach to improve process capability through process improvements and restructuring is also very important. SCV should not be restricted within transaction-related information [20], and operational excellence in the supply chain can secure the ability to operate efficiently and effectively, as planned for the entire supply chain process. In order to acquire operational excellence, both reactive and proactive approaches are very effective, and the outcomes are expressed as various process capabilities.

This research proposes that supply chain visibility is a level where we can predict the viable degree of the supply chain plan, and the visibility level can estimate process capability using a Z score in Six Sigma. This paper also devised a mathematical model to quantify the SCV and suggests a quantification methodology to evaluate the visibility level of the overall supply chain. The proposed methodology can facilitate assessing and comparing suppliers, customers, and competitors. This is a practical model that can more objectively and empirically quantify SCV.

Finally, the effects of the performance factors on the process visibility were assumed to be equivalent at the same stage of the supply chain. However, the effects may be different from those across the industry or for other companies (industry-specific or company-specific), depending on the characteristics. It is necessary to verify the suitability of the proposed model for this issue, and SCV is also needed to conduct an empirical study of the relationship between the distinctive visibility and the financial performance. Therefore, further research is planned in order to expand our proposed model according to these issues.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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