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Improving supply chain performance management: A systematic approach to analyzing iterative KPI accomplishment

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ABSTRACT

Improving supply chain performance has become one of the critical issues for gaining competitive advantages for companies. This paper proposes a framework using a systematic approach to improving the iterative key performance indicators (KPIs) accomplishment in a supply chain context. The proposed framework quantitatively analyzes the interdependent relationships among a set of KPIs. It can identify crucial KPI accomplishment costs and propose performance improvement strategies for decision-makers in a supply chain. A scenario of a large retail company is also discussed to explain the application of this framework.

1. Introduction

In the context of a dynamic supply chain, continuously improving performance has become a critical issue for most suppliers, manufacturers, and the related retailers to gain and sustain competitiveness. In practice, supply chain based companies (e.g., Dell, Wal-Mart, Samsung, Toyota, Lenovo, Gome, etc.) have used different performance management tools to support their supply chain strategies. Monitoring and improvement of performance of a supply chain has become an increasingly complex task. A complex performance management system includes many management processes, such as identifying measures, defining targets, planning, communication, monitoring, reporting and feedback. These processes have been embedded in most information system solutions, such as i2, SAP, Oracle EPM, etc. These system solutions measure and monitor key performance indicators (KPIs) which are crucial for optimizing supply chain performance.

Performance measurement is critical for companies to improve supply chains' effectiveness and efficiency [3,22]. Decision-makers in supply chains usually focus on developing measurement metrics for evaluating performance [3,12]. In practice, once the supply chain performance measures are developed adequately, managers have to identify the critical KPIs that need to be improved. However, it is difficult to figure out the intricate relationships among different KPIs and the order of priorities for accomplishment of individual KPIs. As a matter of fact, determination of priorities within a given set of KPIs has become a bottleneck for many companies in their endeavors for improving their supply chain management (SCM). As these problems have received relatively less attention in previous research [22], significant gaps remain between practical needs and their effective solutions. To address these issues, our research proposes a systematic approach that helps analyze and select the right KPI groups and strategies for their accomplishment, for improved supply chain performance.

The rest of this paper is organized as follows. In Section 2, we articulate the challenges of supply chain performance improvement both in theory and in practice. Section 3 presents the proposed framework for analysis of supply chain performance management, and a systematic approach to assigning priorities to different KPIs, based on the cost of iterative improvement of each KPI. Section 4 discusses an illustrative application of this methodology in supply chain management by a large retail company. Finally, Section 5 gives conclusions and discusses limitations, unsolved problems and possible directions for future research.

2. The challenges of supply chain performance management

Improving supply chain performance is a continuous process that requires both an analytical performance measurement system, and a mechanism to initiate steps for realizing KPI goals; herein we call the mechanism to achieve KPI goals as “KPI accomplishment”, which connects planning and execution, and builds steps for realization of performance goals into routine daily work. To measure supply chain

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performance, there are a set of variables that capture the impact of actual working of supply chains on revenues and costs of the whole system [21]. These variables as drivers of supply chain performance are always derived from supply chain management practices [21]. After identifying KPIs, managers have to achieve improvement in them, through continuous planning, monitoring and execution. According to the results of selected KPIs' accomplishment, managers may create current reports on KPIs, to compare multiple plans of supply chain management. In this performance management cycle, there are many challenges, both in performance measurement, and its improvement.

2.1. Intricate performance measures in a supply chain

Many metrics used in supply chain performance evaluation have been designed to measure operational performance, evaluate improved effectiveness, and examine strategic alignment of the whole supply chain management [3]. Individual measures of supply chain performance have usually been classified into four categories: quality [3,22], time [4,22], cost [4,12], flexibility [1,3]. Furthermore, they have also been grouped by quality and quantity, cost and non-cost, strategic/operational/tactical focus, and supply chain processes [12,22]. However, since many measurement systems lacked strategy alignment, a balanced approach and systemic thinking [3,8], they had difficulty in systematically identifying the most appropriate metrics. To address this problem, some researchers have used Balanced Scorecard (BSC) and Activity Based Costing (ABC) methods to evaluate supply chain performance [16]. Other researchers have also proposed similar balanced frameworks, such as Performance Measurement Matrix, results-determinants framework, performance pyramid, etc. [19]. From a process perspective, the Supply Chain Operations Reference (SCOR) model has been developed to facilitate construction of a systematic supply chain performance measurement and improvement tool; it has often been recognized as a systematic approach for identifying, evaluating and monitoring supply chain performance [17]. In the SCOR model, a balanced performance measurement system at multiple levels, covering five core supply chain processes (i.e. Plan, Source, Make, Deliver, and Return), was developed [4,13,17].

However, measurement models (i.e. extended BSC and SCOR) for supply chain performance evaluation have their limitations. First, there are too many individual measures being used in the supply chain context. For example, Shepherd and Gunter [22] have summarized 39, 22, 35, 28 and 8 single supply chain performance indicators related to cost, time, quality (or reliability), flexibility and innovativeness respectively. Though these measures offer valuable information for decision-making, selecting and trading off so many measures to obtain effective and crucial improvement strategies is a difficult task for different supply chain participants. Second, these models do not provide definite cause–effect relationships among numerous (and hierarchical) individual KPIs. Although existing models (e.g., BSC) do illustrate the cause-and-effect relationships between different goal-related KPIs [18], they are inadequate for quantitative analysis of the intricate intertwined relationships. Traditional BSC and SCOR models generally assume that KPIs are uncoupled. These approaches could describe business operations well, and serve as a good communication tool, but they are not effective in improving overall performance by accomplishing the critical KPIs. For many managers, who try to allocate resources efficiently and achieve multiple supply chain performance goals, this becomes the bottleneck.

2.2. Determination of importance of performance measures

Determination of importance of individual performance measures is another challenge for decision-makers in SCM. Specifically, there are two difficult issues managers face while implementing a well-built performance measurement system. First, since many measurement systems are static (i.e. not dynamic), they often lag behind the constantly varying contexts in supply chains. Once the measurement systems have been established, they are rooted, and remain unchanged, for a long time. But in the dynamic supply chain environment, some measures actually get *outdated* and yet remain *entrenched*, especially the preset KPIs. Second, few measurement systems have a systematic method for prioritizing the measures [19] and, therefore, many companies have difficulties in figuring out ways of adapting their continuously changing strategic objectives and meeting the requirements of the dynamic decision-making environment. It is critical for performance measurement systems and related criteria to be updated and evaluated constantly [3,22].

Recently, some decision-making tools have been used to solve problems of performance metrics' trade-off by weighing the importance of different KPIs. One of them is use of the Analytic Hierarchy Process (AHP) approach, as a quantitative decision-making tool for linking the scorecard's KPIs to the overall mission, objectives, and strategies [13,16]. However, it is argued that AHP is not stable in its theoretical foundation, and could cause revisions in decision-makers' preferences because a pairwise comparison matrix fails to perfectly satisfy the consistency required by the AHP approach [7]. Meanwhile, using AHP is only to determine the “weight” or relative importance of individual KPIs; it does not specify the relationships among KPIs and their role in accomplishment efforts, which are very important factors for continuous supply chain performance improvement in a dynamic environment.

Another decision-making technique is grey relational analysis, which has been extended to analyze the financial performance of businesses, instead of using the traditional statistical methods. Kung and Wen [15] applied the weighing of grey relational matrix to select significant financial performance measures. Similar to the AHP approach, grey relational analysis is used at strategic levels, but not to dynamically select and tradeoff KPIs within a variable supply chain environment. And then the grey relational analysis depends more on the correlation degree of factors that actually generate a grey relational grade, without considering any related strategies and activities. In other words, grey relational analysis has not been adopted to make decisions in a wide range of dynamic situations.

2.3. Performance improvement work dependencies and conflicts

Once critical KPIs have been identified and selected effectively, another challenge is that it is difficult to coordinate the parallel steps required for accomplishment of improvement in identified KPIs. Generally speaking, there are two methodological streams to cope with this problem in previous literature. One stream involves finding out the bottlenecks in the supply chain by implementing the KPIs. For instance, the Theory of Constraints (TOC) [20] is a set of concepts and tools that can be used to implement the widely used continuous improvement management philosophy. TOC improves performance in a system by focusing attention of management on the system's constraints. Thus, by preventing distractions from its primary purpose and concentrating limited resources on efficacious management of the constraint, decision-makers are able to gain significant leverage, sufficient to attain the desired performance levels [20]. In the TOC theory, the method is to find a suitable approach to identify and solve bottlenecks in production, delivery, and service processes. However, the TOC method does not deal with selection of crucial bottlenecks and it doesn't provide the optimal solution of performance improvement for each KPI. Sometimes, the KPIs are coupled or correlated, and it is hard to find the precise bottleneck; improving one KPI might undermine performance of another.

The second stream focuses on performance optimization; the optimization philosophy assumes that there is an optimal performance point, when maximizing or minimizing the identified indicators. Although the performance optimization approach, in theory, is widely accepted by researchers, it is difficult to ensure that an optimized KPI accomplishment strategy is implemented by different members of the supply chain. First, it is difficult to apply in practice, in terms of both data acquisition and computing. It is also difficult for decision-makers to understand in real SCM situations.

Second, it does not take into account the relationships among indicators. Though classified into different categories, different measures in a measurement system are often correlated. The correlations among different measures arise from the inherent internal relations of different SCM processes, and the interdependent influences of different KPIs' accomplishment tasks. Therefore, a feasible methodology of identifying and analyzing the relationships among KPIs related to different SCM processes is important and necessary for improving SCM performance. For supply chain performance optimization, identifying important measures at multiple levels is more important than just maximizing or minimizing the identified indicators. One approach towards evaluating important indicators is the fuzzy logic technique, which is a problem-solving tool for handling vague and imprecise information, to get a definite decision [10]. Although specific applications of the fuzzy logic tool for decision-making have been presented in the hierarchical measurement system [8], there have been few studies of using this tool in performance management, in practice, in comparison to other practical areas (e.g., project management [10]).

In practice, organizations are prone to making rushed decisions, when faced with continuously changing goals and tight deadlines. Managers are short of time to compare all the options when situations demand immediate solutions. Therefore, it is important to describe the mutually dependent relationships among KPIs, and to optimize their accomplishment, based on their complex interdependence. However, most of the previous researches do not provide specific operational procedures for analyzing KPI accomplishment. Considering pros and cons of different methods, this paper provides a framework of supply chain performance measurement and improvement, based on a systematic approach to analyzing KPI accomplishment.

3. A systematic approach to analyzing iterative KPI accomplishment

3.1. An improved model of business performance management cycle

Traditional supply chain performance management has always been approached as a top-down process that conforms to the six steps of the management cycle (see Fig. 1) [6]. Managers derive goals from a corporate strategy, build models to analyze their feasibility, make plans to achieve the goals, and monitor progress toward those goals [6,16]. They analyze deviations and report the results to a senior management team. When the actual results do not match expected outcomes, the management needs to understand the reasons for the variances, and propose corrective actions. Goals and KPIs which are no longer compatible with reality are adjusted. Enterprises often use regular meetings to revisit goals and objectives, refine KPIs, and update operational plans, based on changes in the industry, economic environment, or resource capabilities in their supply chains. They may also add new KPIs or adjust the KPI weights, in response to real situations.

However, since the relationships among KPIs have become more and more complicated in supply chains, it is hard to measure their dependencies and conflicts with the existing methodologies. Once the KPIs and their targets have been defined, managers can hardly change or regulate the KPIs before all the six steps have been implemented. This makes the feedback loop very long. For instance, most organizations have an annual formal planning process called the budget, which involves modeling financial targets and constraints, conducting supply chain negotiations, comparing actual results with previous plans, and refining KPIs and the plans. Since the organization needs to respond faster to new opportunities and threats in the market, it is necessary to shorten the performance management cycle.

Hence, we propose to add a new step, i.e. analyze KPI, into the management cycle, and build a quicker feedback mechanism (see Fig. 1). After the first step, which defines and articulates supply chain KPIs, and the second step, which identifies operational factors and builds management models, the new step is taken. It analyzes the intricate relationships among KPIs and simulates their accomplishment. It also analyzes the feasibility of the KPIs and calculates the financial and operational impact of accomplishing these KPIs and vice versa, providing managers with an integrated view that connects KPIs to operational plans.

3.2. Overview of KPI analysis methodology

To improve supply chain management performance in a systematic way, we propose a methodology of analyzing iterative KPI accomplishments. This methodology implements a small(er) feedback loop among the three major steps of performance management cycle, i.e. set goals, model, and plan. The framework consists of the following steps (see Fig. 2). First, the managers identify and define KPIs and

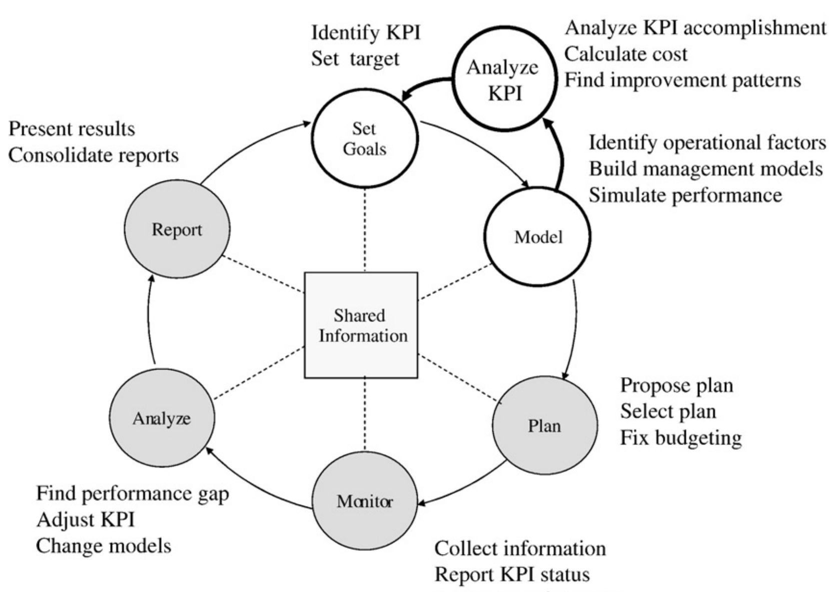

Fig. 1. An improved model of business performance management cycle.

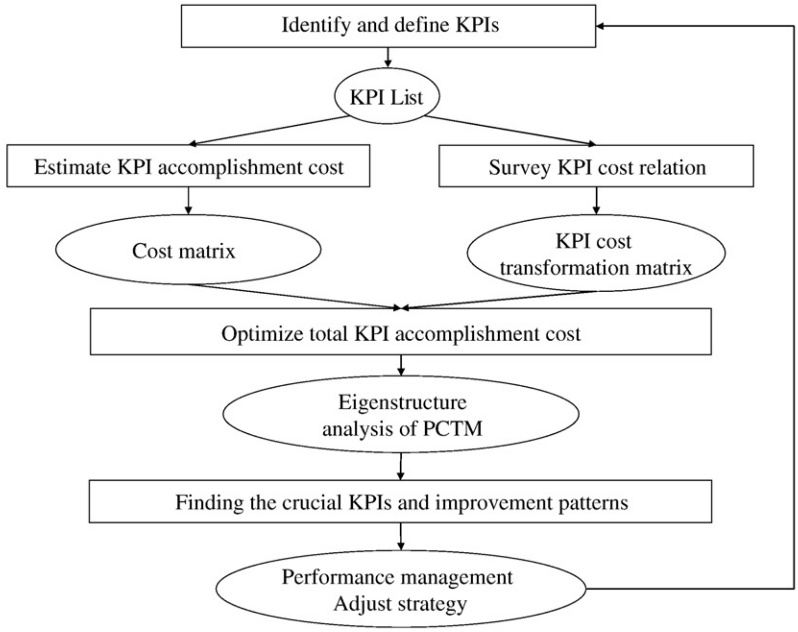

Fig. 2. A research framework of improving supply chain KPIs accomplishment.

their relationships. Then, the accomplishment costs of these KPIs are estimated, and their dependencies are surveyed. Optimization calculation (e.g., eigenstructure analysis, computer simulation) is used to estimate the convergence of the total KPI accomplishment cost, and to find the critical KPIs and their improvement patterns. Then the performance management strategy can be adjusted by interpreting the analysis results. The following sections discuss the details of this methodology.

3.3. Identifying KPI and modeling their relationships

Managers in supply chains usually identify KPIs according to their objective requirements and practical experiences. But to get a systematic or balanced performance measurement, they often turn to some widely recognized models, such as BSC and SCOR. Considering the complicated characteristics of supply chains, our methodology uses a process-oriented SCOR model to identify the basic performance measures and the KPIs. Here, the proposed measurement system includes five categories of measures: resource, output, flexibility, innovativeness and information [1,8,14]. Table 1 gives examples of specific measures of specific categories, which are identified and selected as basic KPIs used in this paper for further analysis.

In practice, most of the KPIs in a supply chain are correlated and have tangled cause–effect interplays [3,14]. This implies that KPI accomplishment is a highly iterative and interactive process. It is common for accomplishment of one KPI to cause extra cost or effort for other KPIs, due to various reasons, such as incomplete information, limited resources, or communication barriers. To represent these relationships, pairs of KPIs having high correlations with each other have to be identified. The nature of such pair-wise relationships can be classified into three categories: parallel, sequential and coupled (Fig. 3). A parallel relationship is a relationship in which two KPIs

Table 1
Level I metrics of supply chain performance based on supply chain processes

Category(Type)	Level I metrics	
Resource	Total supply chain management costs [4]	Information management costs [4]
	Distribution costs [1]	Value-added employee productivity [8]
	Inventory costs [1]	Warranty costs [4]
	Manufacturing costs [1,3]	Return on investment (or ratio of net profits to total assets) [3,22]
	Total turnover costs [22]	
Output	Sales (or profit) [3]	Percent of on-time deliveries [3]
	Rates of stockouts (losing sales) [3]	Perfect of order fulfillment [22]
	Fill rate (target fill rate achievement, average item fill rate) [3,8]	Customer satisfaction [3]
	Order fulfillment lead time [4]	Rates of customer complaints [3,22]
		Planned process cycle time [12]
		Cash-to-cash cycle time [4]
Flexibility	Supply chain responsiveness [3,4]	Delivery flexibility [3,8]
	Manufacturing/production flexibility [8]	New products flexibility [3]
	Procurement flexibility (identified)*	Information systems flexibility (identified)*
	Logistics flexibility (identified)*	
Innovativeness	Rates of sales in new products (identified)*	Supply chain stability (identified)*
	Number of new products launched (identified)*	Process improvement (identified)*
Information	Information accuracy [24]	Information availability [24]
	Information timeliness [24]	Information sharing [1]

Note: *KPIs identified in this paper, by interviews or surveys of companies in China.

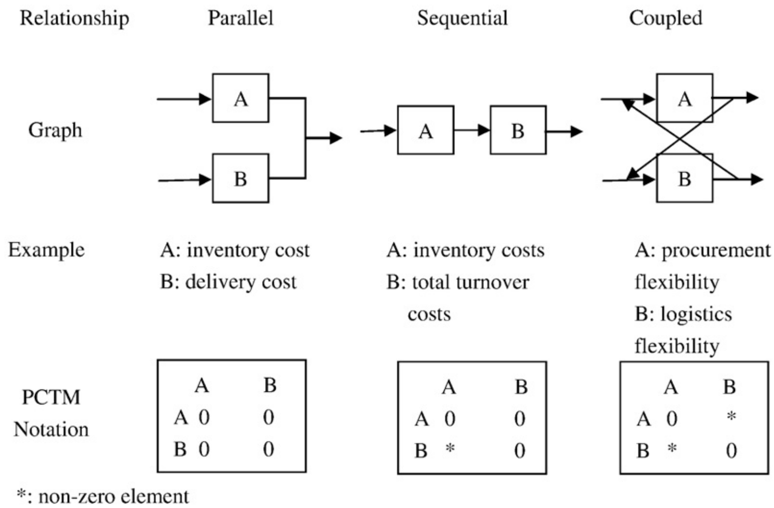

Fig. 3. Relationships between accomplishment efforts for different KPIs.

are independent of each other, i.e. the efforts of accomplishing these two KPIs are not related. A sequential relationship usually implies a simple cause–effect relationship. The effort of accomplishing a KPI causes extra cost to another. For example, efforts made to accomplish the target for 'manufacturing costs' KPI will generally lead to extra efforts and/or expense for accomplishing 'customer satisfaction' KPI, though the reverse dependence doesn't always hold [14]. However, KPIs accomplishment efforts in a coupled relationship are dependent on each other. One example is the relationship between accomplishment efforts of 'manufacturing flexibility' and 'logistics flexibility'.

As shown in Fig. 4, a KPI accomplishment cost transformation matrix (PCTM) represents the interdependencies among KPI accomplishment efforts in a structured manner. To accomplish a KPI in a column causes a certain amount of extra cost for accomplishing a KPI in a row. The non-zero elements in the matrix represent the degree of dependence between accomplishment costs of KPIs, as defined in the next section. There are many ways to generate the PCTM for a supply chain, e.g., brainstorming, historic data, Delphi method, survey instrument, etc.. Whatever means one adopts, one should avoid the trap of 'relationship myopia'. A matrix formulated on the basis of such a mind-set is not only difficult to compute but also leads to meaningless results. We suggest predefining a given set of degrees, as in the Likert scale used in survey instruments [21], and assign a given value to each pairwise relationship. For example, assign 0 to 'no' dependency, 0.05 to 'low' dependency (5% extra cost), 0.10 to 'medium' dependency (10% extra cost), 0.25 to 'high' dependency (25% extra cost) and 1 to 'extremely high' dependency (100% extra cost) (Fig. 4).

Another important matrix in our methodology is the KPI accomplishment cost matrix (PCM), which quantifies the costs of time, money and other resources needed to accomplish KPIs. Each element in the matrix defines the unit cost for accomplishing a certain KPI (Fig. 5). The costs of PCM can be derived by taking activity based costing (ABC) approach [2,5]. This approach fundamentally treats KPIs as cost objects. It uses the costs of the activities as the basis for assigning costs to other cost heads, such as products, services, or customers [5].

3.4. Analyzing KPI accomplishment

Once the actual relationships among the costs of KPIs accomplishments are identified and coded into a matrix named as PCTM, the next step is to simulate the iterative KPI accomplishment process and estimate the total cost. Then the KPIs that are crucial for overall performance improvement can be identified. The algorithm used by PCTM analysis is derived from the eigenstructure analysis. The use of eigenstructure analysis is made in order to observe primary behavior of a complex system, which is also used in many other fields. For instance, the Design Structure Matrix (DSM) method was developed for simulating the impact of improvements on the engineering design process [9,23]. It used eigenstructure analysis algorithm to derive the total process time and simulate to-be/as-is ratio for an engineering design project [9]. The PCTM analysis models KPI accomplishment as a multistage iteration process which has a mathematical structure similar to the DSM model. In our model, the accomplishment costs of all KPIs occur at each iteration, and extra costs are incurred in the next iteration.

M =

	A	B	C	D
A	0	0	0.25	0.1
B	0.1	0	0.1	0.05
C	0.05	0 .05	0	0.25
D	0.1	0	0.1	0

KPI A: inventory costs
KPI B: total turnover costs
KPI C: procurement flexibility
KPI D: logistics flexibility

Fig. 4. KPI accomplishment cost transformation matrix (PCTM).

C =

	A	B	C	D
A	1			
B		0.8		
C			0.7	
D				1.3

A: profit indicator
B: delivery indicator
C: manufacturing flexibility indicator
D: logistics flexibility indicator

Fig. 5. KPI accomplishment cost matrix (PCM).

The KPI analysis methodology makes three assumptions which allow us to perform linear algebraic analysis of the PCTM. Similarly, these assumptions could also be found in Ref. [23]. First, the KPI cost dependencies in PCTM do not change over time. Second, each cost happens once, and only once, in each iteration. Third, in each iteration, the extra cost of a KPI accomplishment is a function of the cost of the previous iteration.

During each iteration, all KPI accomplishment work involves a cost. However, cost of each KPI will cause some extra cost to be incurred for all other KPIs that are dependent on the accomplished KPI, for information and resources. Every iteration stage produces a change in the cost vector according to:

$$r_{t+1} = Mr_t = M^{t+1}r_0 \tag{1}$$

The ratio vector r_t describes the ratio of cost incurred in each stage t, and M denotes the matrix PCTM. The ratio of cost incurred in the initial stage r_0 (t=0) is 1 (i.e. 100%) for all KPIs, meaning that all costs are incurred in full. The overall cost ratio R during the total of T iterations can be calculated by summing up ratio vectors of all stages:

$$R = \sum_{t=0}^{T} r_t = \sum_{t=0}^{T} M^t r_0 = \left(\sum_{t=0}^{T} M^t\right) r_0 \tag{2}$$

The total ratio vector may be scaled with the actual cost of each KPI, i.e. the costs in the diagonal matrix C (i.e., PCM). Thus, the total cost vector CR is:

$$\mathrm{CR} = C\left(\sum_{t=0}^{T} M^t\right) r_0 \tag{3}$$

and the total cost TC is the sum of all elements in the total cost vector:

$$\mathrm{TC} = \sum_{i=1}^{n} (\mathrm{CR})_i \tag{4}$$

We can compare TC with the overall target cost. This can give an estimation of the feasibility of improving the KPIs and the steps required for the same.

PCTM analysis uses eigenstructure to find out where potential improvements of KPI accomplishment could have the maximum effect. For matrix M, we can use the following calculation for further analysis.

$M = V\Lambda V^{-1}$ where $\Lambda$is a diagonal matrix of the eigenvalues of M, and V is the corresponding eigenvector matrix:

$$M^t = V\Lambda^t V^{-1} \tag{5}$$

$$\text{Therefore, } R = V\left(\sum_{t=0}^{T} \Lambda^t\right) V^{-1} r_0 \tag{6}$$

$$\text{And since } \lim_{T\to\infty} \sum_{t=0}^{T} \Lambda^t = (I-\Lambda)^{-1} \tag{7}$$

We can calculate the overall cost ratio by $R = V(I-\Lambda)^{-1}V^{-1}r_0$.

By analyzing the eigenvalues in $\Lambda$and eigenvectors in $V$of R, we can find the critical KPIs which substantially affect the overall cost, and identify feasible improvement patterns.

3.5. Finding the critical KPIs and improvement patterns

Each eigenvalue of PCTM represents the convergence rate for one possible iteration mode in the process. It has been mathematically proved that the iteration mode with the slowest convergence rate has the largest eigenvalue that is always positive and real [23]. According to the algorithm, critical KPIs are those which have relatively greater value in the eigenvector corresponding to the relatively greater real eigenvalues [9]. For example, the eigenvector and eigenvalue of M in Fig. 4 are as follows (see Fig. 6) [23]:

The first eigenvector (i.e. the column in Vcorresponding to the largest eigenvalue in Λ) implies that the corresponding KPI is a critical KPI that can be improved. The critical KPIs, which have larger eigenvector values, are improved, with reduced negative influences on other KPIs and minimization of the total cost of iterative KPI accomplishment. After the critical KPIs are identified, there are two ways to improve them. The first is to decrease their accomplishment costs (the values in PCM), without affecting others. And the second is to reduce dependency of the identified KPIs on other KPIs, and vice-versa.

The eigenvector corresponding to each eigenvalue characterizes the relative contribution of each of the various KPIs to the entire accomplishment, which converges at a given rate. The interpretation of the eigenvalues and eigenvectors for performance improvement problems is similar to the eigenstructure analysis used to examine the dynamic motions of a physical system [23]. The results of the eigenstructure analysis can be used not only to select critical KPIs but also to derive optimal patterns according to specific supply chain objectives, such as lean, agile, flexible and responsive [11]. In this way, a decision support system can use an optimized algorithm to acquire sets of prioritized KPIs, and to identify the improvement patterns, as shown in the scenario in Section 4. Decision makers can select a pattern of critical KPIs that aligns with their supply chain strategies. For instance, if a supply chain focuses on operational efficiency, the matching pattern should include some KPIs that emphasize cost. If the supply chain emphasizes on quick response or flexibility/agility, the matching pattern may cover more KPIs pertaining to responsiveness or flexibility. Based on the improvement patterns, performance goals can be adjusted and suitable KPIs accomplishment strategies, based on existing methods, can be applied. Thus, this analytical model transforms data into valuable information and actionable propositions for improvements.

4. A scenario in a retail supply chain using PCTM

4.1. Background of a SC Company

As a noted electronic appliance chain store, SC Company (SCC) has more than 800 stores in 250 cities in China, and more than 100,000 employees. It has become the biggest distributor for many electronic appliance manufactories. In 2006, SCC completed construction of its marketing network in Level 1 markets, and has since extended it to

$$V = \begin{bmatrix} 0.5968 & -0.7365 & -0.7365 & 0.0614 \\ 0.4607 & 0.0881 + 0.2228i & 0.0881 - 0.2228i & -0.9777 \\ 0.5269 & 0.3901 - 0.3866i & 0.3901 + 0.3866i & -0.0762 \\ 0.3923 & 0.0503 + 0.3099i & 0.0503 - 0.3099i & 0.1857 \end{bmatrix}$$

$$D = \begin{bmatrix} \mathbf{0.2865} & 0 & 0 & 0 \\ 0 & -0.1392 + 0.0892i & 0 & 0 \\ 0 & 0 & -0.1392 - 0.0892i & 0 \\ 0 & 0 & 0 & -0.0080 \end{bmatrix}$$

V: eigenvectors
D: eigenvalues

Fig. 6. Eigenvectors and eigenvalues of PCTM.

richer areas in Level 2 and Level 3 markets. The company is targeting to achieve 30 billion RMB of sales in 3 years. SCC has formulated an e-commerce strategic development plan, which incorporates its experience in marketing, and electronic commerce, into its existing, strong marketing network.

SCC aims to build a new complex supply chain system which would make it the leader in the market for electronic appliances. Several electronic appliance manufactories are participating in the new supply chain. SCC, as a coordinator of the overall supply chain, controls the network, including common chain stores and experience marketing centers, the central warehouses in main distribution areas, production schedules of electronic appliance manufactories, etc. The new supply chain system will take full advantage of legacy information systems of SCC. The system was implemented successfully in the headquarters and some affiliates of the company, and helped improve and integrate management style and functions, operational methods, financial calculations and information sharing between SCC, affiliates, and participating chain stores. SCC has some difficulties in measuring and controlling its supply chain operations. Although SCC has already used BSC and KPIs to model its supply chain system, the managers face the challenges of handling too many intertwined KPIs; the business performance management cycle takes too long a time.

PCTM analysis can facilitate improvement of SCC's SCM. As a leader in electronic appliance distribution industry, SCC has a group of mangers who have sufficient experience in supply chain design, execution and optimization. Considering this background, the supply chain and the corresponding PCTM will not change or fluctuate too much. The creation and optimization processes are stable, which is in accordance with the assumptions of a linear algebraic analysis of the PCTM [9,23].

4.2. Identify and define KPIs with their relationships

We use the proposed framework, as depicted in Fig. 2, to analyze the problems of performance improvement. According to the simplification and optimization principles proposed in the framework, the following five questions need to be answered, to construct a PCTM. 1) Which KPIs are used in supply chain performance measurement system of SCC? 2) What and how strong are the interdependent relationships between these identified KPIs accomplishment costs, when they are simultaneously accomplished? 3) How to optimize the total identified KPIs accomplishment costs, based on their formulated costs relational matrix? 4) What is the order of priority of the selected critical KPIs and which improvement pattern is considered? 5)How to adjust and implement the critical KPI accomplishment strategies?

To answer these questions, we first interviewed employees and managers to identify and define different KPIs, with their coupled relationships. In practice, we need to survey designers, employees involved in implementation, and supply chain experts. Questionnaires and evaluation criteria should be so designed that those involved could analyze each performance indicator, based on their respective participation, experience and area of expertise. Based on our multiple interviews and surveys, we identified 20 measures as KPIs, based on the characteristics of the retail industry, and captured their cause and effect relationships, as depicted in Fig. 7. All measures identified in SCC are classified into four categories: resource, output, flexibility, and innovativeness (see Table 1). Fig. 7 simply gives the cause–effect diagram, which presents interdependent relationships among 20 identified KPIs of four types, and also outlines interrelationships between four types of KPIs.

4.3. Describing the relationships among KPIs accomplishment

Then we observed and surveyed the estimation of cost of each KPI accomplishment, and the iterative relationships. In this step, we use the qualitative cause-and-effect relationships between KPIs to survey and get the cost dependencies, based on work involved in KPIs' accomplishment. Multiple interviews were conducted to introduce the concepts, and to allow the managers who are in charge of operation, strategy, and information systems to specify the relationships among

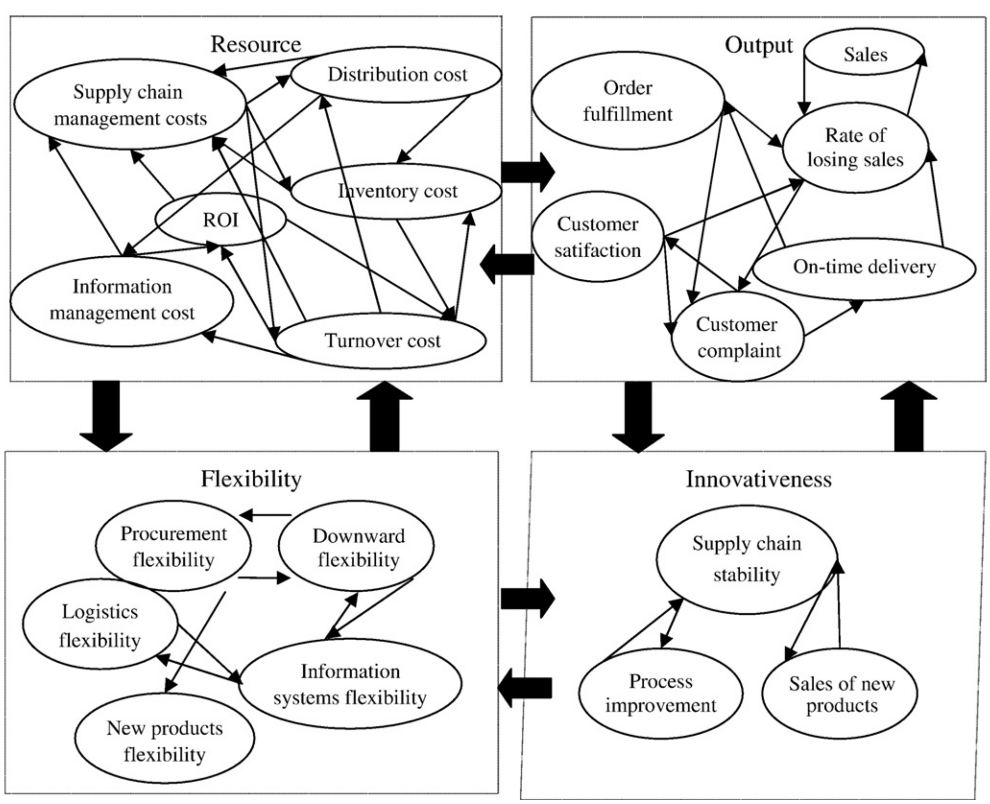

Fig. 7. The cause–effect diagram of 20 performance indicators in the supply chain of SCC.

KPIs accomplishment. To transform the qualitative relationships between KPIs accomplishment work into a definite quantitative matrix, we asked the experts and managers to classify them into three categories: weak (0.05), neutral (0.25), and strong (0.5), as shown in Appendix A, which interprets the interrelationships among 20 KPIs accomplishment. Finally we gained the initial matrix of PCTM analysis.

4.4. Documenting interactions of KPIs accomplishment

Appendix A further illustrates the related drivers of the inherent cause–effect relationships among different KPIs, as depicted in Fig. 7. In Appendix A, corresponding to Step 2 in the proposed framework, each non-diagonal element represents the degree (i.e. neutral, weak or strong) of iteration between two interdependent KPIs accomplishment costs. This treatment could achieve a more agreeable reorganization of the inherent relationships among different KPIs accomplishment. It also aims at simplification of PCTM calculation for the converse matrix. Thus, we deduce that all KPI accomplishment activities are carried out in parallel, simultaneously, and get a static and linear input matrix for PCTM analysis (e.g., no stochastic variation in the iterative process) [9].

4.5. Iterative simulations for KPIs improvement patterns

Based on an initial matrix of 20 KPIs accomplishment, depicted in Appendix A, we can calculate the iterative result by using the iterative algorithm given in formula (1)–(7), as well as the following specific formula of the matrix [23]:

$$r_1 = Mr_0, \quad r_2 = Mr_1, \quad r_3 = Mr_2 \tag{8}$$

Finally, according to the iteratively calculated results, relative eigenvectors and eigenvalues of PCTM, two optimization patterns can be identified, with the two largest positive and real eigenvalues of λ_1 (λ_1=0.9593) and λ_2 (λ_2=0.5401). Table 2 shows the first two eigenvectors with respect to eigenvalues of λ_1 and λ_2, and two iterative cost ratio vectors of 20 KPIs' accomplishment by SCC.

Based on some selected criteria (e.g., KPI numbers=7 or the relative value in one eigenvector>0.17), we get two optimization patterns (the KPI groups composed of two eigenvectors whose values are in **bold**). Pattern 1, as column 1 in Table 2 shows, is mainly formed by the following KPIs: supply chain management cost, inventory cost, ROI, turnover cost, sales, new products flexibility and sales rate of new products. We call this optimization pattern the *efficiency supply chain pattern*, which focuses on increasing sales, decreasing costs and other similar traditional measures, in which enterprises usually produce functional products and have steady demands [11]. Pattern 2, as shown in column 2 of Table 2, is formed by new products flexibility and new products rates of sales. We can call this optimization pattern the *innovational supply chain pattern*. Such a pattern meets the needs of supply chain innovation and flexibility, and especially adapts to supply chain companies which usually produce innovative products and have an uncertain market [11].

From the iterative optimal solutions, we know that SCC, as a traditional retailer, fits in the *efficiency supply chain pattern*, which emphasizes management activities regarding improving efficiency of supply chain operations. Hence, the SCM strategy targets to improve the efficiency of accomplishing reduced management, inventory and turnover costs, and increased ROI and sales by design, or redesign, diagnosis, optimization, etc. Enhancing new product flexibility and rates of sales is necessary for SCC, which also is shown in optimization Pattern 1.

There are two reasons to argue the findings. First, an electronic appliances supply chain involves frequent introduction of new products and needs to adjust to customers' appetites and preferences [11]. Second, SCC is focused on introducing the relatively new

Table 2
Eigenvectors of PCTM and iterative cost ratio vectors in the supply chain of SCC

Key performance indicators (KPI)	Optimization pattern 1: eigenvector of λ_1 (value>0.17)	Optimization pattern 2: eigenvector of λ_2 (value>0.17)	Cost ratio vector r_2 (value>0.7)	Cost ratio vector r_3 (value>0.7)
SC management costs	**0.2305**	−0.0953	**1.0450**	**0.8973**
Distribution cost	0.0900	−0.2492	0.6350	0.4921
Inventory cost	**0.1794**	−0.1688	**0.8700**	**0.7295**
ROI	**0.5788**	0.1571	**2.3575**	**2.1516**
Information management cost	0.1010	−0.0130	0.5225	0.4303
Turnover cost	**0.4447**	−0.1884	**1.7500**	**1.8708**
Sales	**0.2801**	−0.0172	**1.1850**	**1.0841**
Customer satisfaction	0.0468	−0.0683	0.2500	0.2089
Percent of on-time deliveries	0.0484	−0.1685	0.3850	0.2776
Fulfillment of order	0.0095	−0.0504	0.0925	0.0671
Rates of customer complaints	0.0354	−0.1334	0.3000	0.2204
Rates of stockouts	0.0562	−0.1616	0.4075	0.3008
Procurement flexibility	0.1275	0.1202	0.5025	0.4653
Delivery flexibility	0.0827	−0.0529	0.3800	0.3451
Logistics flexibility	0.0987	−0.2355	0.6050	0.5135
NP flexibility	**0.2351**	**0.5668**	**0.7000**	**0.7599**
IS flexibility	0.1000	−0.0323	0.4700	0.4371
Rates of NP Sales	**0.3545**	**0.5974**	**1.1200**	**1.2654**
Supply chain stability	0.1560	0.0866	0.5950	0.5844
Process improvement	0.1677	−0.0275	0.6725	0.6779

Note: SC — supply chain, NP — new product, IS — information systems, ROI — return on investment.

e-commerce concept, which enhances the flexibility and responsiveness of SCC and reflects that SCC wants to become a leader and an example of best practices in the retail industry of China.

It is noticed that all KPIs in Pattern 2 are included in Pattern 1, which means the company should focus on traditional KPIs, as well as innovative KPIs, even in an industry which has short product life cycles and underlines innovation and responsiveness. The managers decided that the innovative KPIs should not receive too much attention. In fact, few companies in China could live on innovation itself, while ignoring traditional financial KPIs. Hence, Pattern 1 should be adopted, which PCTM analytical methodology itself also indicates. Columns 4 and 5 are working vectors in iteration. And it is obvious that r_1, r_2 and r_3 share the same characteristics. The larger elements in r_1 remain larger through out the iteration process.

4.6. Implementing designed strategies of critical KPI accomplishment

Based on the PCTM analysis, we suggest SCC should focus on the following KPIs: ROI, turnover cost, rates of new product sales, sales, new product flexibility, supply chain management cost, and inventory cost, in decreasing order of importance. Once we achieve an order of priority of KPIs, we design ways to improve their accomplishment work and evaluate their (improvement) effects.

Using the analytical methods of PCTM, we can know whether the improved accomplishment of each focused KPI is indeed conducive to overall performance improvement. The accepted method is to test whether using the new PCTM has fewer iterations of looping, or quicker convergent procedures (i.e. to minimize TC). By minimizing iterations of looping, or speeding up iterations of the four attributes, a supply chain could be managed more effectively, using fewer resources. Methods to speed up iterations include introducing new technology and tools to improve efficiency for some activities, such as inventory management and logistics distribution, adopting information systems for integrating database management and network software to speed up internal and external information transmission across the supply chain, and eliminating redundant accomplishment activities.

Methods to minimize iterations of looping include improving communication and collaboration among supply chain partners, such as improving exchange of information, speeding up solving of conflicts, standardizing interaction interfaces, and deepening understanding of optimization processes. Furthermore, we also need to point out that sometime several eigenvalues of PCTM could be larger than 1, which accounts for divergence of iterations, and which means that the feasibility of the simulation project is in doubt. The managing team needs to consider whether to implement such a project. For existing supply chains, simple redesign and optimization can not meet the needs; fundamental redesign of the supply chain is the option.

Then, managers of SCC should implement the designed strategies of KPI accomplishment. Generally, implementation of KPI accomplishment strategies is step-by-step, with caution, because these KPIs are more intensely coupled. One of better KPI accomplishment strategies is accelerating work on the more critical KPIs, while keeping other KPIs unchanged. The accomplishment strategies integrate optimization philosophy into TOC, which helps to achieve continuous performance improvement and approximate a balanced and systematic optimization solution to the improvement problems of SCC. In practical implementation, there are milestones set for each strategic step, to examine whether critical KPIs are indeed improved. Meanwhile, critical KPIs' influences on other KPIs are also checked, to ensure that all critical KPIs are improved. Thus, the analytical result would help managers of SCC to timely adjust their specific strategies, and enable the company to get into a virtuous line to reach its business missions, objectives, and strategies.

5. Conclusions and future work

There is a gap between application and research in supply chain performance measurement and improvement. This research is expected to bridge the gap by identifying critical control factors, by implementing the proposed framework, which further supports decision making. The proposed framework provides an effective approach to managing supply chain performance in a dynamic environment. It solves the performance measures coupling problem by using a systematic approach, while few of previous research works have addressed this problem. The framework and methodology help companies improve performance across the entire supply chain in a systematic manner, through managing complex relationships among the KPIs, and refining the process of determining their KPIs. From the framework, it is feasible to get a holistic view of complex relationships among KPIs, where the cause–effect diagram becomes too complicated because of the large number of KPIs. The framework and methodology offer at least three important theoretical contributions to solve coupled KPI accomplishment problems and provide a good insight for further work.

First, the proposed framework provides a good implementation plan which converts the complex problem-solving into a more operational and quantitative exercise. In a quantitative model, the KPI analysis calculates the estimated cost of each performance management strategy (a set of KPIs), as well as the contribution of the accomplishment of each KPI. For each alternative strategy, it compares the cost with the impact, and likelihood of the associated risks. With analysis of each strategy, managements can afford the time needed to consider all the strategies and avoid the traps of hasty decision-making. In practice, not all facets of supply chain are easy to capture and predict; the framework provides ways of making them more evident and tangible. For different supply chains, the questions and the problems remain open and varied. Nevertheless, applying the framework and its method to the problem of performance improvement would likely provide new insights into ways of enhancement of SCM. It improves the performance management cycle (especially between strategy and planning) by better supporting right resource planning for achieving the supply chain's strategic goals.

Second, the PCTM analysis proposed in this paper is a new extension of the existing eigenstructure analysis methods (e.g., Work Transformation Matrix – WTM – derived from the DSM model) from engineering to business performance management. The analytical optimization approach based on the eigenstructure analysis of KPIs' accomplishment relationship matrix provides the eigenvectors new managerial insights into performance measures selection and improvement. Specifically, it can be used to strengthen the functions of SCM decision support systems, especially for providers of business performance management or business intelligence software, and companies using these decision-support tools for performance improvement. Furthermore, interpretation of eigenvalues and eigenvectors for supply chain performance management problems is more intuitive than the eigenstructure analysis used to examine the engineering problems. Furthermore, opportunities exist to loosen the assumptions and generalize this model to allow for stochastic elements. In this field, some trials on DSM [9,23] have been undertaken. There is possibility of introducing random elements into PCTM to analyze more complicated supply chain contexts. The extensions of PCTM remain an agenda for future research.

Third, the framework and PCTM analysis method can serve as a useful modeling tool in analyzing coupled improvement problems. Once the relationship map exists, suggestions for improvement of KPI accomplishment through PCTM computation become obvious. In general, identification of coupled relationships among KPIs provides a critical piece of information which would help managers of supply chains to better grasp the main facets of supply chain performance and take the right actions to enhance the overall performance. Hence, it is a useful tool for speeding up performance improvements in dynamic supply chain decision-making environments through identifying groups of critical KPIs and improvement patterns through analyzing intricate KPI accomplishment relationship matrix. This approach not only supports organizations to respond to the changes much faster, but also enables the management teams to move forward with confidence.

There are some limitations and unsolved problems, especially for applications of PCTM. First of all, if the environment is changing drastically and frequently, mutually dependent relationships of the KPIs accomplishment may change dramatically and influence the accuracy of PCTM. Hence, we should confine PCTM to moderately changing environments.

Second, the procedural framework and PCTM analysis approach are applied in enterprises where supply chain management has already been actively deployed. If the industry abandons the supply chain management approach, or pays little attention to this aspect, the approach couldn't be used effectively.

Third, results from PCTM should not be adopted as direct decisions, but as supporting information for decision-making. Because different experts may have different opinions of critical indicators, and of different possible solutions; every expert or manager might have his own PCTM. There is no standard answer that can be accepted (and executed) unanimously. Hence, the final decision-making is still left to the managers.

Fourth, this approach can only simulate the SCM iteration and point out sources of KPIs accomplishment costs. It can not influence the details of mechanisms of KPIs accomplishment.

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Appendix A

The PCTM in the supply chain of SCC

SC management cost	*	0.05	0.05	0	0	0.25	0	0	0	0	0	0	0.05	0.05	0	0	0.05	0	0.25	0.25
Distribution cost	0.05	*	0.05	0	0.05	0	0.05	0	0.25	0.05	0.05	0.05	0	0	0.25	0	0.05	0	0	0
Inventory cost	0.05	0	*	0	0	0.25	0.05	0.05	0.05	0	0	0	0	0.25	0.05	0	0.05	0	0	0
ROI	0.05	0	0	*	0	0.5	0.5	0	0	0	0	0	0	0	0	0.05	0	0.25	0.25	0.25
Information management cost	0.05	0	0	0.05	*	0	0	0	0	0	0	0	0.05	0	0	0	0.5	0	0	0
Turnover cost	0.25	0.05	0.5	0.25	0.05	*	0	0	0	0	0	0.05	0	0.5	0	0	0	0	0.25	0.25
Sales	0	0	0	0.05	0	0.25	*	0	0	0	0	0.25	0	0.05	0	0.05	0	0.05	0.25	0.25
Customer satisfaction	0.	0	0.05	0	0	0.05	0	*	0	0	0.05	0.05	0	0.05	0	0	0.05	0	0	0
Percent of on-time deliveries	0	0.05	0.05	0	0.05	0	0	0	*	0.05	0	0.05	0	0	0.25	0	0	0	0	0
Fulfillment of order	0	0.05	0	0	0	0	0	0	0	*	0.05	0.05	0	0	0	0	0	0	0	0
Rates of customer complaints	0	0.05	0	0	0.05	0	0	0.05	0.25	0	*	0	0	0	0.05	0	0.05	0	0	0
Rates of stockouts	0	0.05	0.05	0	0	0	0.05	0	0	0	0.05	*	0	0	0.25	0	0	0	0	0
Procurement flexibility	0	0	0	0	0.05	0.05	0.05	0	0	0	0	0	*	0.05	0	0.05	0	0.05	0.25	0.05
Delivery flexibility	0.05	0	0.05	0	0	0.05	0.05	0	0	0	0	0.05	0.05	*	0	0	0.05	0	0	0.05
Logistics flexibility	0.05	0.05	0.05	0	0.05	0.05	0	0.05	0.25	0.05	0	0.25	0	0	*	0	0.05	0	0	0.05
NP flexibility	0.05	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	*	0	0.5	0.05	0
IS flexibility	0	0	0	0.05	0.25	0	0	0	0	0	0	0	0	0.25	0.05	0	*	0	0.05	0.05
Rates of NP Sales	0	0	0	0.25	0	0	0.25	0	0	0	0	0	0	0	0	0.5	0	*	0.05	0
Supply chain stability	0.05	0	0	0.05	0	0.05	0	0	0	0	0	0	0.05	0.05	0	0.05	0.05	0.05	*	0.25
Process improvement	0.25	0	0.05	0.05	0	0.05	0	0	0	0	0	0	0	0.05	0	0	0	0	0.25	*

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