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Performance Evaluation for the Sustainable Supply Chain Management

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Abstract

Supply chain SC activities transform natural resources, raw materials, and components into various finished products that are delivered to end customers. A high efficient SC would bring great benefits to an enterprise such as integrated resources, reduced logistics costs, improved logistics efficiency, and high quality of overall level of services. In contrast, an inefficient SC will bring additional transaction costs, information management costs, and resource waste, reduce the production capacity of all enterprises on the chain, and unsatisfactory customer relationships. So the evaluation of a SC is important for an enterprise to survive in a competitive market in a globalized business environment. Therefore, it is important to research the various methods, performance indicator systems, and technology for evaluating, monitoring, predicting, and optimizing the performance of a SC. A typical procedure of the performance evaluation (PE) of a SC is to use the established evaluation performance indicators, employ an analytical method, follow a given procedure, to carry out quantitatively or qualitatively comparative analysis to provide the objective and accurate evaluation of a SC performance in a selected operation period. Various research works have been carried out in proposing the performance indicator systems and methods for SC performance evaluations. But there are no widely accepted indicator systems that can be applied in practical SC performance evaluations due to the fact that the indicators in different systems have been defined without a common understanding of the meanings and the relationships between them, and they are nonlinear and very complicated.

In this chapter, the conception of SC performance is first presented, then relevant theories about supply chain performance evaluation are discussed and several common methods of supply chain performance evaluation are discussed. Finally, an evaluation model is presented for SC performance evaluation using 5 dimensional balanced scorecard (5DBSC) and Levenberg–Marquardt Back-propagation (LM-BP) neural network algorithm.

Keywords: SCM, sustainability, performance evaluation, KPI, neural network, 5DBSC, LM-BP

1. Introduction

Served as one of the three major US automobile companies, Chrysler Corporation was founded in 1912. After establishment, the company made a rapid growth due to the constant new car model strategies and shrewd management decisions. Without losing opportunities, a series of cars that can keep pace with the time were designed, developed, and launched. All those efforts demonstrated the courage of the company and have greatly enhanced the company's reputation. As a result, Chrysler was hailed as the designing leader of automobile industry. However, on 30 April 2009, as the company was in crisis, Chrysler Corporation filed for bankruptcy protection. Since then, Chrysler entered bankruptcy proceedings.

In fact, the term "bankruptcy" was not new for this century-old enterprise. In the company's history, there were several times that it was on the verge of bankruptcy, but it had always survived. The economic crisis in 1930s and recession in 2000 had seriously undermined development of the company. The financial deficit forced Chrysler to have massive layoffs, cut back production, and close factories. Rumors about bankruptcy of Chrysler were spread out every now and then. But by taking product diversification strategies and optimizing promotion channels, Chrysler overcame difficulties again and again.

People may ask, what is the exact reason of Chrysler going nearly into bankruptcy frequently?

General view of the US automobile industry is that even if not influenced by financial crisis, the problems that Chrysler accumulated over the years cannot be resolved overnight. The statistical figure shows that compared with BMW, Toyota, and some other automobile companies, extra cost of a single vehicle produced by Chrysler was more than 2000 dollars. In addition to the recognized "high labour costs," Chrysler was also overwhelmed by excessive welfare and retirement policy adopted in 20th century. The most unacceptable problem to the US customers is that Chrysler was never bored with launching high-emission cars Jeep, which was contrary to the historical trend of saving oil and reducing emission. In short, the unsatisfactory performance of the supply chain (SC) made Americans believe that Chrysler will not recover again.

From the above discussion, it can be seen that SC performance evaluation and management are essential for an enterprise if it wants to develop in a long-term stable way. In this chapter, the conception of SC performance is first presented, then relevant theories about SC performance evaluation are discussed, and several common methods of SC performance evaluation are discussed. Finally, an evaluation model is presented for SC performance evaluation using 5 dimensional balanced scorecard (5DBSC) and Levenberg–Marquardt Back-propagation (LM-BP) neural network algorithm.

2. Discussion of performance evaluation of SCM

The biological law—natural selection and survival of the fittest—proposed by Darwin can also be applied to today's fierce business competition environment. Whether an enterprise has the ability to adapt rapid market demand change or not and whether it can deal with the increasing

competition pressure depend on if the enterprise has an effective way of SC management. In order to achieve an effective SC management, SC performance should be evaluated first. Only if SC performance is evaluated accurately and objectively, can existing problems of this SC be identified, and hence, corresponding solutions be found and SC competitiveness be improved ultimately.

2.1. Concept of SC performance evaluation

Nowadays, individual competition among enterprises has turned into group competition among different SCs. During the implementation process of SC management, a great deal of manpower, materials, and financial resources will be consumed and both internal and external pressure from SC partners will have to be dealt with. Hence, a strict SC performance evaluation must be conducted so that shortcomings can be found and corrected. By doing so, SC will be competitive. Serving as a significant part of supply strategy management, performance evaluation will help the enterprise or the organization to understand the daily activity performance of the SC, based on which, a long-term development strategy can be made.

Therefore, it is not difficult to understand the definition of SC performance evaluation: adopting certain SC performance evaluation indices, compared with a unified evaluation standard, using quantitative methods of statistics and operations research to comprehensively evaluate SC performance and costs in a period of time in accordance with regulated procedures in an objective, just and accurate way[1].

SC performance evaluation should serve the goal of the SC. Evaluation objects should cover the whole SC as well as each member of SC. Also, interior and exterior performance of an enterprise and comprehensive SC performance are involved in the performance evaluation which are revealed by all kinds of indicators relating to operation and relationships. From the time point of view, evaluation can be classified as prior, middle, and afterwards evaluation [1].

2.2. Principles and function of SC performance evaluation

Operation performance of the whole SC and members of the SC can be revealed by a good SC performance evaluation system: if logistics processes among the enterprises are reasonable, whether the quality and costs of the SC products are ideal or not. For example, if one supplier on the SC is individually evaluated, then the lower the product price is the better. However, considering such a low-priced raw material will jeopardize final product quality, increase production costs, and overall profit of the whole SC will be damaged, choosing this supplier will not be an appropriate decision.

In order to evaluate operation performance of logistics system objectively and accurately, some following principles must be complied with [2]:

1. Main point of performance evaluation should emphasize on the key performance indicators. To analyze these indicators, mathematical or information tools should be used.

2. Indicators that can reflect SC business processes should be used.

3.   Indicators should not only reflect the performance of an individual enterprise but also the subsystem and the whole SC. This is important to achieve the sustainable SC management (SSCM).

4.   Immediate evaluation methods should be used as much as possible, for doing so is more meaningful than analyzing afterward.

5.   Make sure that goal of SC performance evaluation and goal of the overall SC strategy are consistent, otherwise, SC performance will not make considerable contributions to the strategic goal.

6.   Indicators that support the strategic goal should be chosen.

7.   One of the final targets of each SC is to make customers satisfied. In order to fulfill the real demand of customer, it is necessary for managers to understand what the demands are; meanwhile, they should also have a clear understanding about the SC performance from the customer point of view. Effective SC performance evaluation can play the following roles in the SC management process [2]:

   1. Deficiencies and shortcomings can be found and relevant improving measures can be identified.

   2. Serve as evaluation indicators of SC business processes reengineering, setting up time, cost, and performance-based SC optimized system will provide decision basis for sustainable SC management.

   3. By evaluating the member enterprise of a SC, excellent enterprises will be motivated, troubled enterprises will be removed, and new partners will be attracted. Meanwhile, partnerships will be evaluated too during SC performance evaluation.

3. Performance evaluation indicators

Companies not only have to concern themselves about environment issues but also have to deal with social performance pressures such as social reputation and social responsibility. As a result, although SSCM is a relatively new concept, it developed rapidly in the recent years.

Concept of sustainable SC should be understood before conducting management. There is not a unified definition about sustainable SC yet, but some of the definitions are recognized by most scholars, which are shown as follows.

Seuring and Müller defined SSCM as the management of material, information, and capital flows as well as cooperation among companies along the SC while taking goals from all three dimensions of sustainable development, that is, economic, environmental, and social, into account which are derived from customer's and stakeholder's requirements [3].

Carter and Rogers believed that SSCM can be defined as the strategic, transparent integration, and achievement of an organization's social, environmental, and economic goals in the

systemic coordination of key interorganizational business processes for improving the long-term economic performance of the individual company and its SCs [4].

Based on conceptions mentioned above, it is not difficult to find out that the inclusion of sustainability into the theory of SCM is most often based on the triple bottom line approach [5] that calls for equal consideration of all three pillars of sustainability, namely, environment performance, economic performance, and social performance. This means evaluation indicators can be chosen accordingly.

3.1. Environment indicators

In the area of SSCM, environment performance has been given a lot of attention. Sometimes, there are tradeoffs between environment performance and economic performance. For instance, ecofriendly materials may cost more so that it will have impact on economic performance. However, environment performance can positively influence economic performance. For example, waste products or some certain emissions can be recycled as raw materials for other products, and minimizing waste can also help to saving cost. In addition, an eco-friendly production method will save companies from a large amount of pollution control costs or environmental penalty. Therefore, in order to achieve a win-win target rather than tradeoffs, managers should evaluate SSC from an integration point of view and achieve balance between environment investment and cost efficiency. Here are some possible indicators for the environment performance evaluation: greenhouse gas emission, water usage, energy consumption, waste generation, the use of hazardous and toxic substance, waste recycle etc [6].

3.2. Economic indicators

Whether in SSCM or in SCM, economic performance has been paid a lot of attention. One final goal of a SC management is to make profit. Otherwise, it will be eliminated from the market. When considering sustainability of a SC, focal companies might be able to justify the long-term economic benefits of designing environmental and social initiatives at the supply-chain level and present a business case for sustainability, where firms benefitted financially from engaging in sustainability practices [7]. Various studies using SC modelling have traditionally focused on the economic aspects of the SC with cost minimization (or profit maximization) and service level maximization as the most predominant objectives. Here are some possible indicators for economic performance evaluation: SC cost (SC costs may include the cost of procurement, production, opening, and operating facilities as well as transportation and storage costs), cost reduction, service level (service level may include customer satisfactory, product/quantity flexibility, and backorders), SC revenue, SC profit, etc [8].

3.3. Social indicators

Among all the three aspects in SSCM, social performance is the most difficult one to assess, the indicators of which are not easy to be quantified and are often prone to subjectivity. However, social performance evaluation is indispensable. Not only can social issues threaten the company's brand image but they also impact the economic viability of the entire SC [8].

Several instances of this nature have been frequently reported in the past, jeopardizing the reputation of large multinational corporations such as Wal-Mart, Nike, Gap, and H&M through the violation of union rights and the use of underaged workers [9]. In the other way round, a well-performed social practice is capable of enhancing a company's image and reputation, which serves as a significant resource in the SC, and helps to increase market adaptability of products and services. Here are some possible indicators for social performance evaluation: labour practice and decent work, gender diversity and harassment, human rights, occupational health and safety, fair trade, fair labor metrics, etc [10].

SC performance evaluation has traditionally been dominated by indicators such as cost, quality, delivery, and flexibility. In the circumstances of considering sustainability, these indicators are still very important but not necessarily in a dominant role. Also, indicators introduced in this section are relatively rough and only give a general idea of SSC performance evaluation. Detailed indicators are explicated according to different performance evaluation theories in Section 4.

4. Performance evaluation theory and method

Due to the fact that SC combines suppliers, manufacturers, distributors, dealers, and customers with information flow feed forward and material flow feedback, it is largely different from the current enterprise management model as from enterprise operation performance evaluation and analysis.

Based on the basic features and goal of SC management, SC performance evaluation is capable of properly reflecting the overall SC performance as well as of each member enterprise on the SC rather than a single supplier. During the evaluation process, not only performance of a certain member enterprise of SC should be evaluated but also the influences that the certain member enterprise has on the upper or lower SC member enterprises should be evaluated. SC performance evaluation normally includes the following aspects: the overall SC performance, each member enterprise performance, partnership among member enterprises of the SC, and incentive level toward member enterprises.

To fulfill above targets, ordinary enterprise performance evaluation theories are not fully applicable; this section will mainly illustrate several common SC performance theories, and they are using driving factors to evaluate SC performance, key performance indicator, SC balanced scorecard, and SC operations reference model.

4.1. Using driving factors to evaluate SC performance

Sunil Chopra from Northwestern University of America and Peter Meindl from Stanford University proposed the following idea: by deeply studying the cross function driving factors that influence SC performance (facilities, inventory, transportation, information, purchasing, and pricing), SC performance can be improved through responsiveness and efficiency of the SC logistics [11].

4.1.1. Facilities

Facilities refer to the actual location of the SC, storage sites, assembly, or processing sites. Production sites and storage sites are the main two facilities. Decisions about facilities role, location, production capacity, and flexibility have a significant influence on SC performance. For instance, to improve responsiveness, an automotive parts distributor will locate their warehouse close to their customer, although it may lower their efficiency. Or a distributor with high efficiency will decrease their warehouses to maintain efficiency despite that it will influence responsiveness.

Here are some indicators to evaluate facilities performance [11]:

1. Production capacity—the maximum production quantity of a facility.

2. Utilization—the ratio between currently being used production capacity and total production capacity of a facility. Utilization has an impact on unit cost of production and a variety of delay. When utilization is improved, unit cost will be reduced but delay will be more.

3. Theoretical production process time/cycle—production time required for one unit with the circumstances of no delay.

4. Actual average production process time/cycle—the actual average production time for all products in a certain period of time such as a week or a month. Actual production process time/cycle including theoretical time and all the delays.

5. Process time efficiency—the ratio between theoretical time and average production process time.

6. Product variety—the number of products or product series in a production facility. The bigger number, the higher possibility of increasing production cost, and production process time.

7. The top 20% stock keeping unit (SKU) and customer contribution toward production— the value of the top 20% SKU and customer consumption volume should be measured, the result of 80/20 principle (top 20% factors contribute to 80% of the capacity) shows that profit may come from using the top 20% specific procedures to process the top 20% and the other 80% of the products.

8. Processing/adjustment/shutdown/idle time—processing time of a facility/prepare and adjustment time of a facility/time that facilities cannot operate due to damage/idle time because of no product demand.

9. Average production volume—the average yield of each batch of product. A large volume usually comes with a low production cost and high SC inventory.

10. Production service level: ratio between punctually completed orders and the total orders.

4.1.2. Inventory

Inventory consists of raw material inventory, work in progress (WIP), and finished goods. Changing inventory strategy will greatly influence SC efficiency and responsiveness. For example, clothing retailers may own a large amount of stock to quickly respond and satisfy customer demands. However, enormous stock will increase retailer's cost so that efficiency will be decreased, which will have an undesirable influence of responsiveness in return.

Increasing inventory helps SC to improve responsiveness toward customers. A high level of inventory makes an enterprise easier to take advantage of economies of scale, lower cost of production, and transportation, yet by doing so inventory carrying costs will be increased. Managers should review the following inventory indicators that influence SC performance [11].

1. Average inventory—average volume of carrying inventory during a period of time. Average inventory should be measured according to unit, demand days, and monetary value.

2. Overdue inventory products—a great number of stocks owned by an enterprise. This indicator may be used to identify oversupplied products or the reason for high level of inventory (price discount or a low delivery speed).

3. Average replenishment quantities—average quantities of each supplement orders.

4. Average safety inventory—the average quantities of stocks when replenishment arrives. Average replenishment quantities were measured by SKU. Cargo unit and demand days should also be known. Average replenishment quantities were measured by SKU. Cargo unit and demand days should also be known.

5. Seasonal inventory—cycle stocks and safety stocks carried by an enterprise to meet the seasonally changing demand.

6. Fulfillment ratio—ratio between orders were fulfilled on time by inventory and total orders. Fulfillment ratio is determined by the average demands units (per thousand, million) rather than average time to fulfill the order.

7. Out of stock time ratio—ratio between time of a certain product which has no stock and time it has inventory. This ratio can be used to estimate the demand during the period of out of stock.

4.1.3. Transportation

Using a rapid mode of transport will increase responsiveness and transportation cost, but the advantage is stock carrying cost can be decreased. Managers should review the following transportation indicators that influence SC performance [11].

1. Average inbound transportation costs—certain percentage of product sales or sales costs that are put into manufacturing facilities. It is ideal but very difficult to measure this indicator by units that are invested in. Average inbound transportation costs are often included in sales costs. It is beneficial to allocate these costs by a supplier.

2. Average scale of loading stocks to storage—average units or price that finished product put into a storage.

3. Loading costs of inbound transportation of each time—average transportation costs of each purchasing. Together with average scale of loading stocks to storage, larger economies of scale can be created by inbound transportation.

4. Average outbound transportation costs—delivery costs of product sent from manufacturing facilities to customers. This indicator is usually measured by proportion of sales. It is beneficial to allocate these costs by a customer.

5. Average loading scale of outbound transportation—average units or price of each delivery from the manufacturing facilities.

6. Loading costs of outbound transportation of each time—average transportation costs of each delivery. Together with average loading scale of outbound transportation, larger economies of scale can be created by outbound transportation.

7. Transportation mode ratio—ratio between a certain transportation mode and all kinds of transportation mode (per unit, US dollar or RMB). This indicator can be used to estimate excessive use or inadequate use of a certain transportation mode.

4.1.4. Information

Effective information is capable of helping an enterprise improve its responsiveness and efficiency. Information factor may optimize performance of other factors. Usage of information was based on a strategy orientation supported by other factors. Accurate information not only helps an enterprise improve their efficiency by decreasing inventory and transportation costs but also optimizes responsiveness by adjusting supply and demand on the SC. Managers should review the following information indicators that influence SC performance [11].

1. Forecasting period—it refers to a period of future time that the prediction is against. Forecasting period must equal to the lead time of decision-making triggered by forecast.

2. Update frequency—update frequency of each forecast. Forecast updating should be more frequent than decision amendment so that influence toward decision brought up by big changes can be weakened and corrective action can be adopted.

3. Prediction error—deviation between actual demand and forecast value. Prediction error is a measurement and an action toward uncertainty (safety inventory or excessive production capacity).

4. Seasonal factor—the degree to which actual demand is higher or lower than average demand in a season.

5. Planning fluctuation—difference between planning product volume or inventory and the actual ones. These fluctuations can be used to identify shortages and surpluses.

6. Ratio between demand changing and order changing—standard deviation of coming demand and supply orders. If the standard deviation is less than 1, it suggests "bullwhip effect" may exist.

4.1.5. Purchasing

The target of making a decision to purchase is to increase the total profit that is shared by the SC. Purchasing has an influence on sales, service, production cost, transportation cost, and total profit. If a third-party logistics can make more profit than first and second logistics, outsourcing logistics is meaningful. In comparison, if third-party logistics is not able to increase SC profit or it is very risky to outsource logistics, the enterprise should remain the function of SC. Managers should review the following purchasing indicators that influence SC performance [11].

1. Due days—days from which the supplier finished their tasks until they get paid.

2. Average purchasing price—the average price of purchasing a certain product or a service. When calculating average purchasing price, final result should be based on quantity-weighted of each price.

3. Range of purchasing price—it refers to price fluctuation during a period of time. This indicator is used to make sure if purchasing price is related to purchasing quantity.

4. Average purchasing quantity—average quantity of each purchasing. This indicator is used to make sure if the total quantities of purchasing from each region are adequate.

5. Due deliver ratio—ratio between due deliver time and total deliver time.

6. Supply quality—product quality provided by the suppliers.

7. Supply lead time—days from ordering until successful delivery.

4.1.6. Pricing

All the target of pricing decision should be focused on increasing profit for the enterprise. To achieve the target, it is necessary to understand the cost structure of SC activities and values that are created by those activities. For instance, daily low-cost strategy is able to stabilize demand and result in an efficient SC. Some other pricing strategy may reduce SC costs and maintain an even earn market share. Price discrimination is able to attract different customers with different demands. As long as these strategies are conducive to increasing revenue or reducing costs, enterprises should adopt a bit of both.

Managers should review the following pricing indicators. For menu pricing, each indicator should be reviewed respectively according to each section of the menu [11].

1. Profit margin—profit percentage of revenues. Enterprises need to look at various profit margin indicators in order to optimize pricing. Specific indicator dimension including type of profit margin (gross profit margin, net profit margin, etc.), profit scope (cargo unit, product series, department, enterprise, etc.), and type of customers.

2. Sales unpaid days—average time to receive cash after sales.

3. Increment of fixed cost of each ordering—the increment is independent of ordering scale. The increment consists of cost of transformation methods in plant, ordering processes, and transportation costs of delivery scale which is independent of purchasing company.

4. Increment of variable costs per unit—the costs will increase as the ordering scale changes. Costs including cargo pickup costs and variable production costs in manufacturer's plant.

5. Average selling price—the average price of a completed task of SC in a period of time. When calculating average sales price, final result should be based on quantity-weighted of each price.

6. Average ordering quantities—average quantities of each ordering. Average ordering quantities, ordering scale, increment of fixed cost of each ordering, as well as increment of variable costs per unit can help to estimate contribution of a certain completed task of SC.

7. Selling price range—the variation range of the highest and lowest selling price per unit of product within a specific period.

8. Range of sales volume in a period of time—the variation range of the highest and lowest sales volume within a specific period (day/week/month).The purpose of reviewing this indicator is to understand the correlation between sales volume, selling price, and potential chance to adjusting selling price to change in sales volume as time pass.

Driving factors and indicators are summarized in the following **Table 1**

Driving factors of SC	Indicators
Facilities	Production capacity
	Utilization
	Theoretical production process time/cycle
	Actual average production process time/cycle
	Process time efficiency
	Product variety
	The top 20% SKU and customer contribution toward production
	Processing/adjustment/shutdown/idle time
	Average production volume
	Production service level
Inventory	Average inventory
	Overdue inventory products
	Average replenishment quantities
	Average safety inventory
	Seasonal inventory
	Fulfillment ratio
	Out of stock time ratio

Driving factors of SC	Indicators
Transportation	Average inbound transportation costs
	Average scale of loading stocks to storage
	Loading costs of inbound transportation of each time
	Average outbound transportation costs
	Average loading scale of outbound transportation
	Loading costs of outbound transportation of each time
	Transportation mode ratio
Information	Forecasting period
	Update frequency
	Prediction error
	Seasonal factor
	Planning fluctuation
	Ratio between demand changing and order changing
Purchasing	Due days
	Average purchasing price
	Range of purchasing price
	Average purchasing quantity
	Due deliver ratio
	Supply quality
	Supply lead time
Pricing	Profit margin
	Sales unpaid days
	Increment of fixed cost of each ordering
	Increment of variable costs per unit
	Average selling price
	Average ordering quantities
	Selling price range
	Range of sales volume in a period of time

Table 1. Driving factors and indicators of a SC€.

4.2. Key performance indicator

Serve as a monitor of the macro strategy implementation result, key performance indicators (KPI) refer to operational tactical target that are decomposed from macro strategy of an enterprise and have impact on strategy development as well as overall performance of a company [12]. KPI is a popular international tool of measuring company operation performance and managing strategic target, the establishment of which will form a responsibility oriented system management mode. In addition, KPI is quantifiable and is agreed in advance, meanwhile, it is also a significant indicator system that is used to reflect the degree of organization target accomplishment. Briefly, KPI is an effective management tool which can motivate a company to create more value. The specific functions of KPI are as follows [12]:

1. As company strategy target decomposed, senior managers are able to have a clear understanding about the business operating conditions of company's most critical value creation.

2. Changing degree of key performance driving factors can be reflected effectively so that managers can timely diagnose operation problems and take relevant actions.

3. Qualitative and quantitative indicators can be distinguished. A strong impetus will be given to implementing company strategy.

4. Key, important operation behavior can be revealed so that managers can focus on those business that have the greatest driving force toward company performance.

5. Determined by senior managers and agreed by participants who will go through the exam, as a result, an objective foundation for performance management and communication between leader and member is provided.

To fulfill the above functions, choosing KPI should be in line with the following principles: indicators should be easy to understand, explain, and convey. They should be clear rather than ambiguous, instead of random ones. Meanwhile, it is necessary that indicators should be able to control and enforce, not just some decorations. Finally, they should be quantifiable and trustworthy [12].

To deal with the fierce competition, a lot of manufacturing enterprise outsource their logistics operation. As a result, evaluating performance of a logistics service provider is particularly important, which is also a basis of supplier selection. In an organization system, the majority of large manufacturing enterprises have set up SC management department or logistics operation department to be in charge of logistics-related business. In large manufacturing enterprises, line transportation, warehouse management, and regional distribution are the three relatively independent logistics segments. Hence, to evaluate SC performance, KPI can be chosen from the three segments. Summarization of indicators is in **Table 2**.

Category	Indicators
KPI of line transportation	Plan execution rate P
	Plan remaining rate R
	Delivery delay rate D
	Accidental freight A
	Timely transfer document rate T
	Document accuracy E
	Service quality S
KPI of warehouse	Correctness of cargo receiving and sending out C
	Document accuracy E
	Timely transfer document rate T

Category	Indicators
	Stock damaged ratio Q
	Warehouse quality W
	Customer satisfaction M
KPI of regional distribution	Fulfilled orders on time rate F
	Accidental freight A
	Document accuracy E
	Timely transfer document rate T
	Customer satisfaction M

Table 2. Indicators of logistics operation performance.

4.2.1. KPI of line transportation

Focused on the two eternal themes of logistics service security and punctuality, following indicators of line transportation are chosen [12–15].

(1) Plan execution rate P (Vehicle arrival rate)—This indicator refers to ratio between program execution time of logistics service provider within response time and program number (Vehicles arrive on time and comply with loading requirement). Response time means the time that vehicles of logistics service provider or company's own supply department need to arrive assigned location and loading cargo after delivery plans were issued by logistics department. Response time of a forwarding station in a whole nation is two days. Program execution rate $P1$ on the first day must reach 85%, the rest must all be finished on the second day which means accumulated program execution rate on the second day must be 100%. Plans cannot be finished on the day must be recorded in remaining plan table. Plans that cannot be finished in two days must be otherwise recorded and make a special (urgent) plan.

(2) Plan remaining rate R

This indicator mainly assesses the plans remaining time of logistics service provider or SC department when they carry out plans. Plans that cannot be finished on the first day can be seen through plan execution rate of the second day, but plans that also cannot be finished on the second day cannot be shown. So plan remaining rate is used for reviewing time and days of remaining plan.

(3) Delivery delay rate D

Since the moment cargo has been loaded on the vehicle, logistics service provider or SC department will urge driver to deliver cargo to the destination safety, timely, and completely except for the force majeure (war, earthquake, large collapsed pavements, and mountains covered by snow). Other reasons (traffic jam, broken vehicles, and traffic accidents) cannot be served as exceptions. Ratio between delayed deliver plans and the total plans of a certain month is called delivery delay rate D. Punctual delivery ratio will be 1-D.

(4) Accidental freight *A*

It can be divided into accident loss ratio and freight accident ratio. Ratio between accident lost value and cargo total value is called accident loss ratio. Freight accident ratio refers to the ratio between accident times and total delivery times.

(5) Timely transfer document rate *T*

This indicator mainly assesses if the following documents are transferred timely by the forwarding station—statistic document, daily plan remaining document, overdue vehicle statistic document, reimbursement, and statistic document of delivery list.

(6) Document accuracy *E*

Documents must be filled in according to required format and should be kept clear and tidy. For those hand-filled documents, handwriting should be clear, neat, and without alterations. After documents are filled in, they should be strictly and carefully checked to eliminate mistakes.

(7) Service quality *S*

This indicator is mainly used to review service awareness and service attitude of logistics service provider or SC department.

4.2.2. KPI of warehouse (transit warehouse)

Warehouse management focuses on customer service, which is mainly about customer satisfaction and warehouse management quality. Six indicators and relevant daily used documents are determined [12-15].

(1) Correctness of cargo receiving and sending out *C*

Total amount of receiving and sending out cargo minus wrong receiving and sending out cargo amount, than compared to the total amount, the proportion of which will be correctness of cargo receiving and sending out.

(2) Document accuracy *E*

This indicator has the same meaning with "Document accuracy *E*" in transportation indicators.

(3) Timely transfer document rate *T*

This indicator mainly assesses if the following documents are timely transferred by transit warehouse: receiving list, product inventory daily report, transit warehouse shipments feedback form, spare and ware out parts daily form, damaged cargo maintenance monthly form, finished product age analysis monthly form, spare and ware out parts monthly form, inventory of advertising materials monthly report, defective products processed monthly report, etc.

(4) Stock damaged ratio Q

Ratio between amount of goods damaged in warehouse and total amount of goods. Because damage occurred in warehouse, warehouse manager should take responsibility for the loss.

(5) Warehouse quality W

It is expressed as the storage environment, fire safety, cargo stacking, and goods identification should comply with certain provisions of the transit warehouse management. Performance of this indicator can be evaluated through onsite inspection. Storage environment refers to inside and outside hygiene of a warehouse, pest control, storage temperature and humidity control, and cargo maintenance in warehouse. Fire safety is determined by whether the firefighting facilities are complete and useful and whether the firefighting measures can be implemented without any potential risks. Cargo stacking and goods identification should be in line with warehouse management rules.

(6) Customer satisfaction M

Customer satisfaction is quantified by number of effective customer complaints. In reality, customer satisfaction consist of four aspects: loading waiting time, service attitude of warehouse management (including guards, warehouse keeper, billing staff, and porters), ability to deal with abnormal situations, and time of repeated complaints.

4.2.3. KPI of regional distribution

Indicators of regional distribution focus on distribution network, promptness of delivery is considered, and five indicators and related documents are determined [12–15].

(1) Fulfilled orders on time rate

On time refers to cargo that were delivered to the destination within the requested time (e.g., 24 hours) after orders were received. Fulfillment refers to the delivered cargo that can meet the requirement of the order in respect to SKU standard and quantity. Delivery time will be counted after logistics supervisor issues delivery list. Cargo must be delivered within requested time (e.g., 200 km within 12 hours, 200 km–400 km within 24 hours, more than 400 km within 36 hours) to the specific department or the customer.

(2) Accidental freight A

This indicator has the same meaning with "Accidental freight A" in transportation indicators.

(3) Document accuracy E

This indicator has the same meaning with "Document accuracy E" in transportation indicators.

(4) Timely transfer document rate T

This indicator mainly assesses if the following documents are transferred on time: second distribution process control report, second distribution daily report, and second distribution summarization report.

(5) Customer satisfaction M

Customer satisfaction is quantified by a number of effective customer complaints. Service awareness and service attitude of carrier are the main concerns.
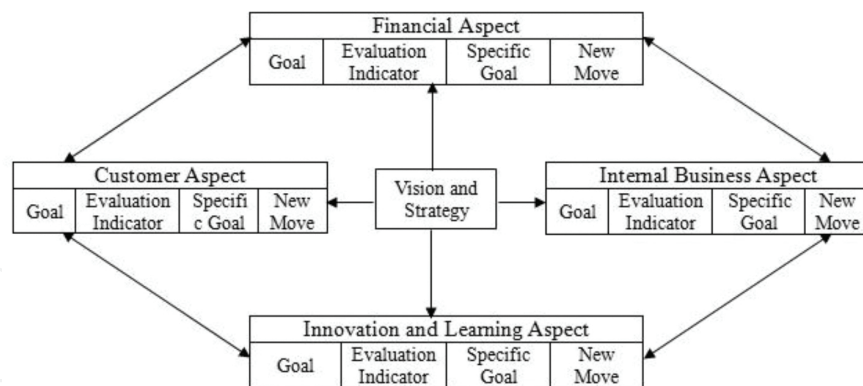
4.3. SC balanced scorecard

The conception of balanced score card (BSC) was first proposed by Robert S Kaplan and David P Norton in 1992. BSC clearly stress on enterprise vision and motivator to accomplish enterprise strategy. Then, strategy motivators are transferred into specific target and measureable indicators which include external and internal measurement as well as objective and subjective factors. BSC consist of four distinctive aspects: financial aspect, customer aspect, internal business aspect, innovation, and learning aspect (**Figure 1**) [16]. Meanwhile, BSC can be used to decompose target of the whole enterprise into targets of each level of the enterprise.
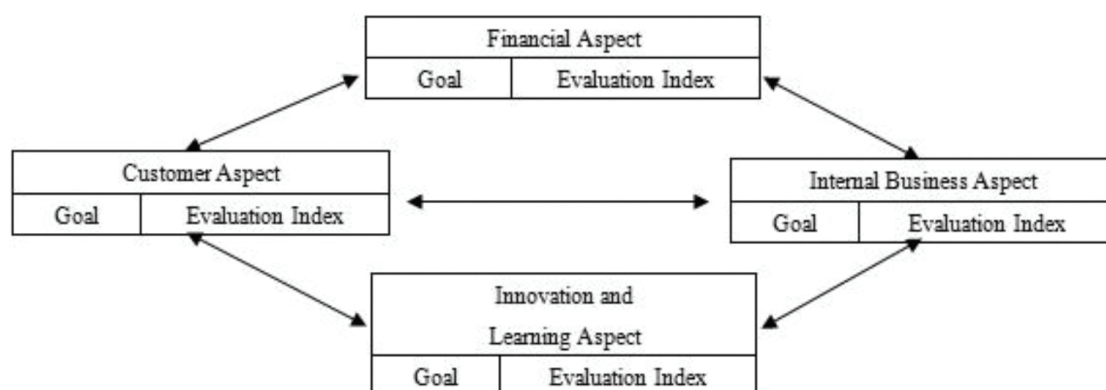
Figure 1. Balanced Scorecard.

BSC can be used not only as a tool of behavior controlling and historical performance estimation but also for clarifying and spreading corporate strategy and individual plan, department plan, and organization plan. These plans can be linked together so that their common goal can be accomplished. BSC emphasizes on integration of financial and nonfinancial measurement, and these indicators must be blended into every management level so that managers can understand their factors that lead to decisions and behaviors. A propagating, communicating, and learning system is constructed rather than a simple traditional controlling system to keep the goals in consistency due to the fact that performance indicators are shared in the management system. Hence, BSC has become a foundation of new strategic management system and become a bridge which correlate long-term strategy and short-term behavior (**Figure 2**) [16].

Figure 2. Relations of Balanced Scorecard and Enterprise Vision.

Since 1998, with the condition of new economics which was represented by information technology, BSC has the ability to promote enterprises to expand and grow and has been vigorously applied in strategy management. Before BSC was invented, there was no standard framework or systematic theory about SC performance evaluation methods. Application of BSC exactly covered this shortage. Brewer and Speh were the first ones to explore how to apply BSC in SC performance and proposed a new tool to evaluate SC performance, SC balanced scorecard (SCBSC). Based on SC business processes, SCBSC start from enterprise strategy and can be used to evaluate enterprise operation performance comprehensively by linking performance indicators and enterprise strategy together. As a result, core competitiveness of the enterprise is fostered. Framework of SC performance was connected to the four dimensions of BSC by Brewer and Speh so that basic structure of SCBSC was defined (**Figure 3**) [17].

Figure 3 shows that, Brewer and Speh set up a connection framework between SCM and BSC. SC performance management including four aspects: (1) goal of SC management, (2) customer profit, (3) financial benefits, (4)SC improvement. There is a one-to-one correspondence between chain performance management and 4 aspects of BSC [17]. For example, the ability of a SC to fulfill its goal can be revealed from its inner operation. Emergence of SCBSC is a breakthrough in SC performance evaluation. Beforehand, BSC and SCM were seen as two separate management tool. Employees are incented to work correctly under the background of SC concept when managers aware that evaluation process of BSC can be adopted into SC performance evaluation [17].

Thus, advantages of SCBSC can be further indicated as follows [17]:

1. SC itself is a combination of multi departments or multi organizations. Its executive performance must be reached by the members working together from inside and outside of an organization. The causal relationship of 4 aspects of BSC makes a clear description about how an effective cooperation can be reached by members from different organizations and how multi-functional operations can be coordinate to achieve their mutual goal.
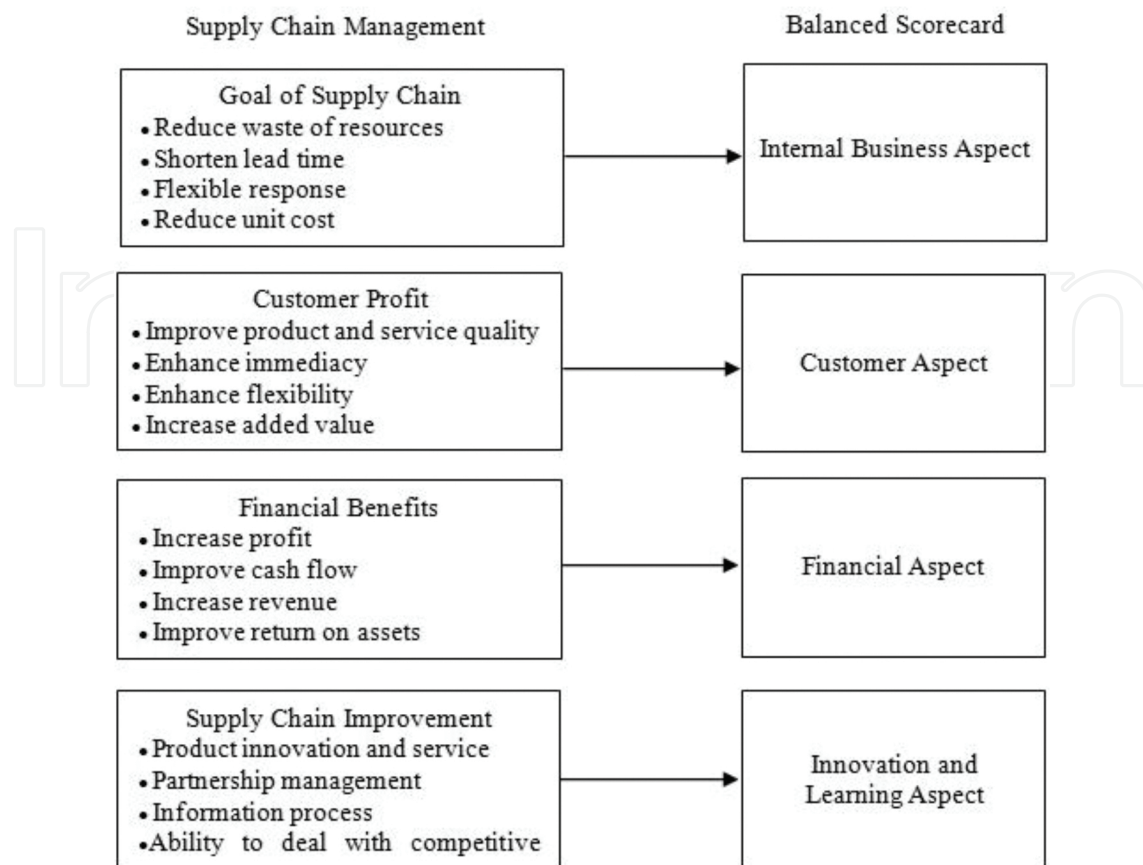
Figure 3. Connection between SC Management and BSC.

2. The "balanced" conception of BSC advocates that performance evaluation of an enterprise and its partners on SC should be conducted simultaneously, which is the same from management goal of SC performance evaluation.

3. Indicators and final goal of BSC can be special designed to fit different SCs which can still connect with enterprise strategy, so BSC can be used in a very flexible way.

4. Different member from different management level such as supervisors and staff can have a clearly understand about their operation goal from BSC rather than consider it as a reward or punishment tool.

Some indicators of the 4 aspects were proposed to reflect goals and tasks of different SCBSC angles. These indicators are not comprehensive even deficient for some specific SCs. Most of the indicators are rarely used in BSC, instead, they are more maneuverability in the diagnosis level.

4.3.1. Internal business aspect

An outstanding process decision of an organization will generate outstanding customer performance, which means optimizing internal business process is very crucial for an enterprise. Combining internal business process, finance, and customer goal, SC should focus on

two kinds of brand new internal business process operation [17]:(1) to rationalize existing relationship of each member in each process and shorten operation process cycle while reducing cost. α(12)Forecast and respond to customer demand. SC operation should not be confined to a short-term point of view but should develop market and make product innovation so that customers can be attracted.

(1) Product improvement and innovation process evaluation [16–19]

In a traditional SC, R&D is considered to be some kind of a subsidiary or a support to a business rather than a fundamental factor to determine pricing. The existing problem is that, on the one hand, the input–output relationship is ambiguous, on the other hand, there is insufficient attention paid to product innovation and product development and design are neglected. However, serving as a long-term influence factor to SC value, R&D is necessarily to be evaluated. Indicators including ratio between new product sales and total sales, time that need to develop new product and percentage of first time designed product that can meet all the requirements of customers.

(2) Operation process evaluation [16–19]

Operation process is a short-cycle process, which contains all the contents starting from receiving customer orders and ending at putting the product on sale or offering service. Detailed evaluation indicators consist of efficiency of SC effective leading time, flexibility of SC production time, target cost reaching rate, SC operation quality, and perfect order completion rate.

4.3.2. Customer aspect

One of the main goals of SC management is to provide its customer persistent and stable profit. Therefore, one core of SC management is customer management, which means fully understanding customer demand and evaluating to what extent the customer demand has been satisfied. Customers are mainly concerned with four aspects [17]: time, quality, function, and service cost. The total circulation time of SC order fulfillment can measure the time that SC needs to meet the customer demand. Quality has always been a critical competition mean; however it is no longer a necessary strategic competition advantage but a compulsive existence. Function and service costs are significant factors to maintain customers and attract new customers. In addition to these aspects, customers are very sensitive to their product cost. During transaction process, product price is only part of cost, transaction cost that happened when dealing with suppliers is also part of cost. When chosen, these indicators mainly reflect customer demand. Indicators are not only those that reveal customer value or customer feedback but also can be those that reveal some specific aspects such as service quality, flexibility, and cost.

(1) Total circulation time of SC order fulfillment [16–19]

This indicator evaluates overall respond time to customer orders of a SC, which includes ordering and receiving time, time of placing material to production, time of goods from

production until ready to be delivered, time of goods delivered and customer signing receipts, and time of customer confirming that goods have been received.

(2) Customer maintenance rate [16–19]

Persistent profit of a SC comes from the core customer. If a SC wants to remain or increase market share, the most convenient thing to do is to maintain existing customers, try to manage relationship with customers and satisfy customers as much as possible. Customers should be allowed to participate in production design and development so that they will become a lasting profit source. In addition to keeping existing customers, customer loyalty should be analyzed during SC management. Of course, if an enterprise wants to gain more profit, constantly strategy of expanding customer scope should be made on the basis of existing customers.

(3) Customer acceptance to SC respond flexibility [19]

This indicator is used to evaluate the acceptance degree of SC customization and respond flexibility.

(4) Customer sales growth and profit [16–19]

It is shown as SC product annual customer sales increment and profit rate. These kind of indicators mainly reflect performance of three aspects of downstream of the SC: (1)annual sales growth year by year, (2)if profit of service provided to special customer will increase as partnership enhanced, (3)if service accepted base is increasing. Expanding sales and attracting new customers are both new profit increase points.

4.3.3. Financial Aspect

Although SC evaluation is process-oriented and focus on nonfinancial indicators, financial still is the center of SCBSC, which means final success of a SC should also be a financial one. Achieving operation goal by greatly lower cost and increase marginal income ratio so that cash flow is optimized and more profit will be gained, at the same time, a higher capital recovery ratio will be gained. Improved performance in the other three aspects can guarantee a long-term benefit in the financial aspect, hence, optimizing this aspect of a SC is still a priority.

(1) Capital return rate of a SC

Divide customer profit by the average used assets of the SC during a period of time, and capital return rate can be calculated, which reflects degree of value-added of the asset.

(2) SC profitability

This indicator shows profitability of a SC and is an important indicator in evaluating financial performance. By measuring the ratio between net profit and total income, SC profit can be effectively calculated so that overall performance of a SC will be promoted to improve. Therefore, evaluating this indicator will help an enterprise to have a clear understanding about finance contribution rate of the SC.

(3) Cash turnover ratio

Cash turnover ratio is a key indicator which links all the processes of a SC. It mainly evaluates cash flow condition of all the processes including raw material, labor, WIP, finished goods, and profit gained of the SC.

(4) SC total inventory cost

In a SC, inventory cost includes raw material cost, WIP cost, finished product cost as well as in-transit inventory cost [2]. Nowadays, due to the more and more demanding customer requirements, inventory management becomes more and more important to lower SC cost.

(5) SC inventory days

SC inventory days indicate the days that capital are occupied as inventory in SC operation.

4.3.4. Innovation and learning aspect

There are mainly three sources for innovation and growth: talents, system, and organization procedure [2]. In these three aspects, the goal of BSC is to reveal the gap between existing talents, systems, procedures, and the required ability to accomplish breaking performance [2]. SC's sustainable competitiveness is directly correlated with SC's future development ability. In the evaluation model, finance evaluation, customer evaluation, and inner business process evaluation are mainly to analyze current competitiveness of the SC, but the goal of success is changing constantly, and SC performance must be capable of indicating sustainable competitiveness. A SC has to make continuous improvement and innovation, explore and integrate internal and external resources of the SC while improving existing procedures, product/service quality, and new product develop ability due to the increasingly tough global competition. SC improvement and innovation are a dynamic process. Each SC needs to pay attention to potential threats and opportunities in external market at any time and redefine core value. This includes redesigning products and its processes through SC integration, effective regulation on interorganizational activities as well as continuous improvement in SC information process management, and SC partners can all share precise information that are needed for decision-making. The following indicators are chosen.

(1) Profit growth rate

Profit growth rate indicates development potential of an enterprise. Difference between profit of current period and previous period divided by profit of previous period is profit growth rate.

(2) Information sharing degree

It is believed by most scholars that "bullwhip effect" can be avoided by information sharing from upstream and downstream so that SC performance can be improved [2, 11–12]. Sales, forecast data, and technology data are shared by members of dynamic alliance to prevent information distortion, improve customer feedback efficiency so that supply and demand can be connected, coordinated, and be quickly responded.

(3) New product research and development cycle

This indicator consists of two aspects, one is the ability of replacing product and the other one is the ability of innovating processes. The ability of replacing product includes new product quantity, product technology reservation, and patent application. The ability of innovating processes is understanding about individual demand tendency of customer of the SC and on the basis of which to adjust processes. This innovation include not only restructuring process but also selecting the superior member and eliminating the inferior member.

4.4. The SC operations reference model

In 1996, in order to help enterprises to implement a more effective SC and to transit from function management to process management, two consulting companies from Boston, America, Pittiglio Rabin Todd & McGrath (PRTM) and AMR Research (AMR) led to the establishment of SC Council (SCC), and illustrated the SC operations reference model (SCOR) in the very year. This model integrated well-known business process reengineering (BPR), benchmarking and process measurement, and a multifunctional SC performance evaluation system was constructed. Currently, SCOR model has been released in eight editions, which are the first standard SC operation reference models that can served as diagnose tool of SC and covers all the industries.
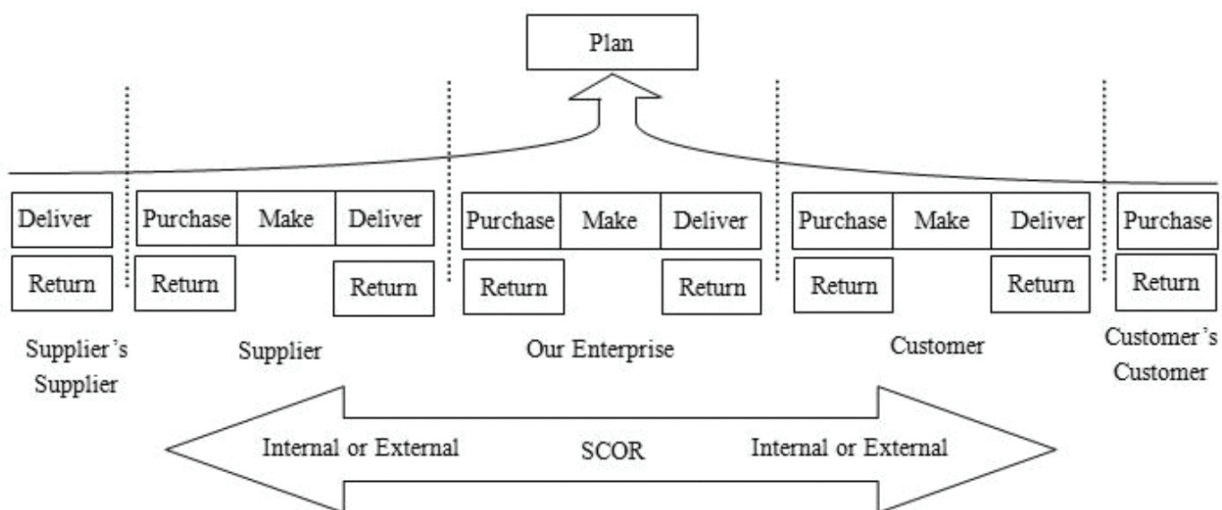

Figure 4. SC Operations Reference-Model.

SCOR has the ability to help a SC enterprise to understand current situation and future anticipation, quantify operational performance among peers, and set up internal goal. There are mainly four indicators in SCOR [20]: (1)reliability of SC, (2)flexibility and reaction, (3)cost, (4)capital. The first two indicators evaluate performance in customer service and the last two evaluate inner performance of an enterprise. In SCOR, all processes in the entire SC are considered and each member of the alliance will be evaluated systematically rather than a certain enterprise is evaluated, which makes the SC become more transparent with a higher performance. Framework of SCOR is founded on five management processes: plan, purchase, manufacture, deliver, and return [11] (**Figure 4**).

SCOR can be classified into three layers according to its detailed degree of definition [15]: top layer, configuration layer, and process unit layer. Each layer can be used to analyze the operation of integrated SC. After the first three layers, there are the fourth layer, the fifth layer, and the sixth layer [11]. They are more detailed and specific that belonging to different enterprises, so definition of these layers are not included in SCOR [11].

4.4.1. First layer of SCOR (top layer)

SC are divided into five processes by the first layer: plan, source, make, deliver, and return, where return include return of raw materials and return of products [11]. Raw materials will be returned to the suppliers. Return of product means returned goods are received and dealt with (**Figure 5**).
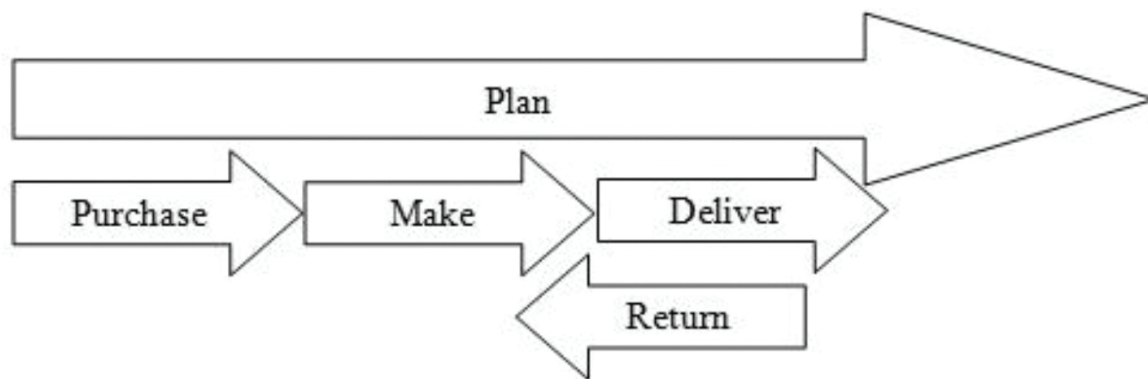

Figure 5. Basic Process of First Layer of SCOR.

Basic strategy decision can be made according to the following indicators after first layer analysis of SCOR [20–23].

(1) Delivery performance—on (ahead of) time order complete/plan finish rate.

(2) Delivery speed—delivered rate within 24 hours after finished goods warehouse receiving orders.

(3) Order complete performance—production flexibility, capital turnover period, capital turnover rate, lead time of order completion, SC respond time, inventory days of supply, all orders fulfillment rate, value-added productivity, and warranty and after-sales costs.

4.4.2. Second layer of SCOR (configuration layer)

The second layer consists of 30 possible core process scopes of SC [22]. An enterprise can choose the standard process unit of this layer to construct their SC. Every product or product model will own their own SC. Detailed configuration of the layer processes of SCOR is showed in **Figure 6** [11].
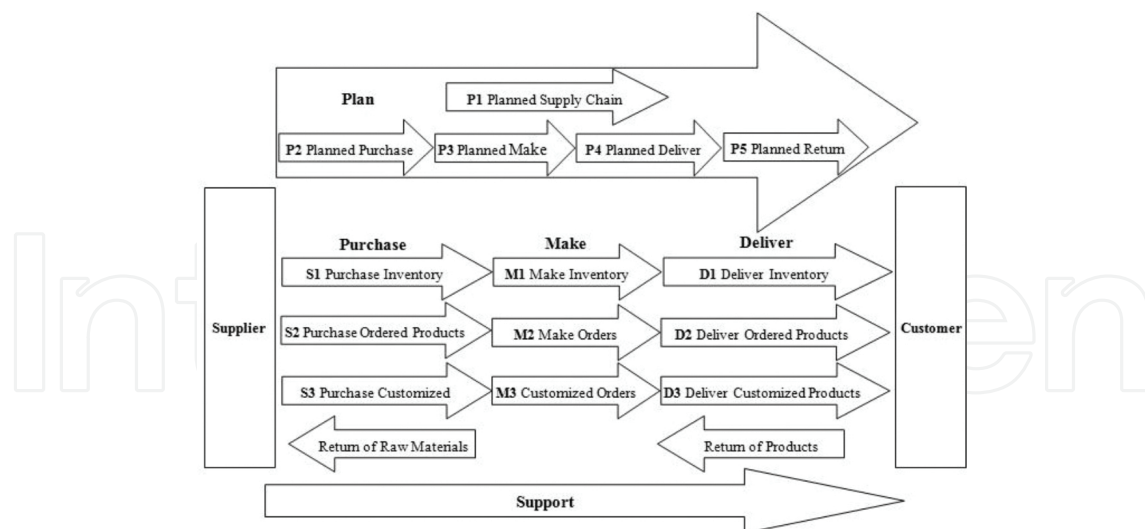
Figure 6. Configuration Layer Process of SCOR.

4.4.3. Third layer of SCOR (process decomposition layer)

The third layer of SCOR is process decomposition layer, which shows the details of process unit classified in the second layer and offers information that is needed by an enterprise to make a successful plan and set up other SC improvement goals [11]. Planning content of this layer include process definition, goals evaluation, best implementation, and necessary software ability to achieve best function [23]. Operation strategies should be adjusted on this layer.

4.4.4. Fourth layer of SCOR (implementation layer) [20–23]

The fourth layer and its following layers are all implementation layers which do not belong to the scope of SCOR. When special requirements for SC improvement are raised, every definition of the fourth layer is based on enterprises' own situation, the particularity makes it impossible and unnecessary to define the special units in industry standards. In implementation layers, process units decomposed from the third layer will be decomposed again by each enterprise based on their current SC management so that competition advantages will be gained and business process changes can be adapted to.

4.5. Analytic hierarchy process

Analytic hierarch process (AHP) was proposed by American operational research expert, T. L. Saaty in the 1970s, which is a multiobjective decision-making method combines qualitative analysis and quantitative analysis [24]. The main idea of AHP is through analysis of factors related to complex system and their mutual relations, simplifies the system into an orderly hierarchical structure so that factors can be incorporated into different layers [24–25]. Then, judgment matrix will be built in each layer and relative weight of each layer will be gained. Finally, global weight against overall goal of each factors that belong to different layers will

be calculated so that basis for decision-making and selection will be provided [24–25]. Since AHP was introduced, due to its feature of dealing with decision-makings in combination of qualitative and quantitative analysis, it has been paid a lot of attentions and has been rapidly and widely used in various fields of social economy areas such as energy systems analysis, urban planning, economic management, and research evaluation. However, AHP also has some limitations [26]: (1) it relies on experience of people to a large extent, so it can at most exclude severe inconsistency of thinking process rather than the possibility of existence of serious one-sidedness of decision-makers. (2)Comparison process and judgment process of AHP are rather rough that cannot be used to deal with highly precise problems. As a result, AHP can be mostly regarded as a semiquantitative (or a combination of qualitative and quantitative) approach [26].Weakness of AHP have been improved and perfected by many scholars, and some new theories and methods have been formed such as group decision, fuzzy decision theory, and feedback control theory, which have become new research hotspots in recent years.

4.6. Analytic network process

Analytic network process (ANP) was proposed in 1996 also by T. L. Saaty, professor of University of Pittsburgh of United States [27]. ANP is a new decision-making method developed from AHP, which allows the coexistence of indicators that can quantify or are difficult to quantify [28]. Correlations or feedbacks of factors within clusters or among different clusters are also take into consideration [28]. Therefore, ANP is better than AHP in decision problem reflection and description. A system will be divided into two parts, one is control hierarchy which consists of problem goal and decision criteria where decision criteria are considered to be independent of each other [29]. Control hierarchy is a typical AHP structure and weight of each criteria can be gained by traditional calculation of AHP method [29]. The other part is network hierarchy, which consist of element groups that are subjected to control hierarchy.
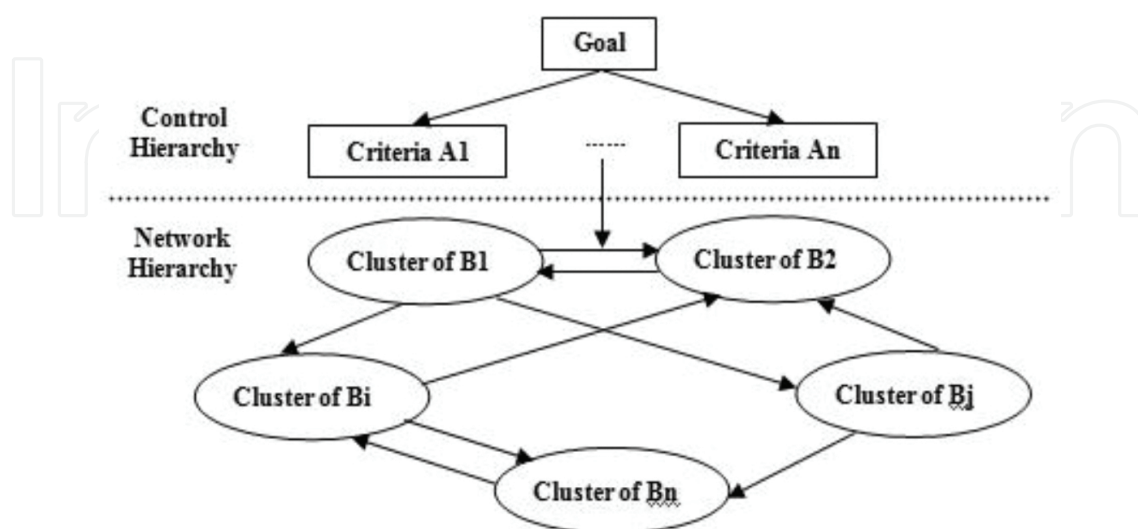

Figure 7. Basic ANP Structure.

Network consists of elements that interact and multiinfluence each other [29]. Basic ANP structure is shown in **Figure 7**.

4.7. Fuzzy comprehensive evaluation method

Theoretic basis of fuzzy comprehensive evaluation is fuzzy mathematics. Fuzzy mathematics is a new science proposed in 1965 by American cybernetician L. A. Zadeh, which had a quick development in the last 50 years.

In the natural sciences or social sciences, there are many definitions that are not very strict or are fuzzy. Fuzzy feature mainly refers to the ambiguity of transitions among different objectives [30]. For instance, pollution category of environment quality can be described as "slight pollution, medium pollution, and heavy pollution," a certain ecology situation to survival or adaptability of a certain crop can be described as "favorable, relatively favorable, less favorable, and unfavorable," and these concepts are normally very fuzzy. To deal with these "fuzzy" concept data, fuzzy set theory came into being.

According to requirements of set theory, one object correspond to one set, either it belongs to the set, or it does not belong to the set, and only one or the other. Such a set theory itself is unable to deal with specific fuzzy concepts [30]. Due to this fact, in 1965, American automatic control Professor Zadeh first proposed the concept of fuzzy sets and created the theory of fuzzy mathematics. Currently, fuzzy mathematics have been broadly used in various areas.

Comprehensive evaluation is an overall evaluation of an object that are subjected to several factors, and this kind of problems are all frequently happening in daily life or in scientific work. Product quality assessment, scientific achievement evaluation, and certain crop adaptability all belong to comprehensive evaluation. Inevitably, there will be ambiguity and subjectivity when evaluating objects from many aspects, and using fuzzy mathematics method to conduct comprehensive evaluation will make the evaluation result to remain with the greatest objectivity so that a relatively ideal evaluation result can be acquired [31]. This is where the existing meaning of fuzzy comprehensive evaluation model lies.

Mathematical model of fuzzy comprehensive evaluation can be divided into one layer model and multilayer model, which can be applied to different types of objectives respectively [31].

Evaluation indicators refer to the ones that fuzzy comprehensive evaluation are based on, which are also contained by the objectives. These indicators are various attributes or properties of objectives that are also known as parameters or quality indicators. Because they are capable of revealing the quality of objectives comprehensively, objective situation can be evaluated based on these indicators.

If evaluation objective contains one-layer structured indicators, which means the objective consists of several indicators, quality evaluation can be done based on these indicators [31]. Under these circumstances, it would be appropriate to use one-layer model to evaluate the objectives.

If an evaluation objective contains multilayer structured indicators, which means objective itself is a main factor that contains several subfactors, each subfactor also contains several

indicators, etc [30]. Under these circumstances, it would be appropriate to use multilayer model to evaluate the objectives. When it comes to this situation, each subfactor should be evaluated first based on the indicators that subfactors contain and then the main factor will be evaluated according to the subfactors evaluation result so that overall evaluation result of the objective can be reached.

Complicated casual relationships always existed in SC performance evaluation indicator system [32]. Both qualitative and quantitative indicators make performance evaluation has a fuzzy and uncertain feature [32]. Fuzzy comprehensive evaluation offers a power tool to evaluate this uncertainty and provides scientific basis for rational evaluation decisions.

4.8. Gray relational analysis

Gray system theory is a new mathematic theory which integrates system analysis, modeling, forecasting, decision-making, and control in whole and can be used to solve problems in the condition of insufficient data, incomplete sample, and imprecise information [33]. This ability to deal with incomplete information can fit realistic requirements in a better way and is more effective in an incomplete information environment [33]. Gray relational analysis (GRA) has the ability to develop a part of the information that is already known and to extract useful information, and then it will have a correct understanding about the overall system and control it effectively. Different from traditional statistical methods, it is not necessary for sample data to comply with statistical rules such as normal distribution and T distribution while using GRA [24]. Another significant advantage of this method is that it is able to get satisfactory results through vast changing factors [33]. For reasons mentioned above, GRA is considered to be the best approach in decision-making in modern business environment.

4.9. Markov chains theory [34–35]

Markov chain was named after A.A. Markov, and it is a random process in discrete time which has Markov features in mathematics. In this process, given the current knowledge or information, forecast in the past (the historical time before now) is irrelevant to future (future state after now).

Markov forecast method is the one that predicts the probability of events. Based on the theory of Markov state transition, it predicts changes in every moment (or period) in future based on current situation of an event, which has been widely used in the economic field.

In the condition of SC, each operation strategy of each node enterprise can be adjusted, operation behaviors of enterprises are random, changing trends of which only related to a current state that means SC performance has nothing to do with past performance before the current time. Therefore, Markov chain theory can be used to do research on changing trends of SC performance and forecast the pros and cons of overall SC performance in a future moment.

4.10. Rough set theory [36–38]

In early 1980s, a Polish mathematician Z. Pawlak proposed a data analysis method based on indistinguishable relationship, rough set theory. Rough set theory studies on expression, learning, and summarization of incomplete and uncertain knowledge and data, essence of which is symbol-based machine learning.

Research objective of rough set theory is an objective set (observations and cases) described by multiattributes set (features, symptoms, and characters). Every objective and its attributes have a value to serve as its descriptive symbol. Objective, attribute, and descriptive symbol are the three basic elements of a decision problem. This form of expression can also be seen as a two-dimensional table, the row corresponding to objects, the column corresponding to attributes of objectives. Each row contains descriptive symbols of its corresponding objectives as well as information of objective membership category. Typically, the available information about the object is not necessarily enough to divide its membership category. In other words, this inaccuracy results in distinguishing the capability of objects. Given an equivalence relation between objects, formed by which, leads to unclear relationship of approximate space. Up approximation and down approximation formed by unclear classes are used to describe rough set theory. These approximations correspond to possible maximum objective set and possible minimum objective set that surely belong to a given class respectively. The difference between down approximation and up approximation is a boundary set which contains all the objectives that cannot be exactly determined whether they belong to the given class. Approximation accuracy and quality can be determined by this kind of processing. Rough set method can deal with significant classification problems, all redundant objects, or attribute inaccurate subsets can be approximately classified in a good way so that acceptable quality classification can be reached. In addition, it can also be used in the form of a decision planning set to show all the important relationships among most of the attributes and particular classifications.

4.11. Artificial neural network (ANN) [39–41]

Study work of McCulloch and Walter Pitts in 1940s is considered to be the beginning of modern artificial neural network research. They proposed the first mathematical model of artificial neuron which was used to describe human brain's working principles. Artificial neural network is a smart network constructed artificially based on the understanding of human brain and neural network, which is able to fulfill certain functions. It is an information processing system constructed on the basis of imitation of brain neural network structure and its function. Therefore, research foundation of artificial neural network is understanding about human brain and brain's neural network.

Through research on human brain's neural network, its basic feature can be noticed:

1. Human brain consists of large amount of neurons and neuron connections.

2. Signal transfer strength is determined by neuron connection strength.

3. Neuron connection strength can be changed according to the training of that network received.

4. Signals can bring provocative influences or restraining influences.

5. The cumulative signal effect of a neuron received determines the state of the neuron.

6. Whether cells will be activated rely on the "threshold" of the neuron.

Therefore, here is the basic construction of artificial neural network:

1. Neuron is a unit with multi-input (multiple of dendrites of one neuron connected to other neurons via synapses) and single output (one neuron has only one axon as an output channel) unit.

2. Only when a neuron has a feature of nonlinear input/output characteristics and when the cumulative effect of the received signal in the cell exceeds a threshold, the cell will be activated, then it will send signal to other neurons through the axons.

3. Neurons have plasticity. Signal input strength that cells received from different neurons is adjusted by a corresponding synaptic connection strength.

Artificial neural network is capable of conducting associative inference, parallel processing rapidly, identifying self-adaptively, and simulating human thinking. After scientific training and learning, it is able to find out nonlinear relationship between input and output of a system, so it can be used for intelligent reasoning and forecasts. SC performance evaluation system is a complex evaluation system that comprise a plurality of indicators as well as input and output. Indicators maybe obscure and uncertain. In addition, nonlinear correlation among indicators may exist. To deal with such a complex evaluation system, artificial neural network has been used more and more to construct SC performance evaluation system.

5. An evaluation model of SC performances using 5DBSC and LM-BP neural network algorithm

5.1. Introduction

A SC is a system of organizations, people, activities, information, and resources involved in moving a product or a service from suppliers to customers. SC activities transform natural resources, raw materials, and components into various finished products that are delivered to end customers. A highly efficient SC would bring great benefits to an enterprise such as integrated resources, reduced logistics costs, improved logistics efficiency, and high quality of overall level of services. In contrast, an inefficient SC will bring additional transaction costs, information management costs, and resource waste costs and reduce the production capacity of the all enterprises on the chain. So the evaluation of a SC is very important for an enterprise to survive in a competitive market in the business environment of the globalization. Therefore, it is important to research various methods, performance indicator systems, and technology for evaluating, monitoring, predicting, and optimizing the performance of a SC. A typical procedure of the performance evaluation of a SC is to use the established evaluation perform-ance indicators, employ a numerical method, follow a given procedure to carry out quantita-

tively or qualitatively comparative analysis to provide the objective and accurate evaluation of a SC performance in a selected operation period.

Various research work has been carried out in proposing the performance indicator systems [42–44] and methods [45–47] for SC performance evaluations. But there is no widely accepted indicator systems that can be applied in practical SC performance evaluation due to the fact that the indicators in the different systems have been defined without a common understanding of the meanings and the relationships between them that are nonlinear and very complicated. The methods proposed for applying an indicator system are also difficult to effectively apply for practical SC performance evaluation.

The study of bionics bridges the functions, biological structures, and organizational principles found in nature with our modern technologies. The output of bionics study includes not only physical products but also various computations, social and business management methods that can be applied in different areas. People have learned from the biological system behaviors and structures to design and develop a number of different kinds of natural-inspired optimization algorithms that have been widely used in both theoretical study and practical applications [48–50]. Though there have been various efforts in applying the natural-inspired algorithms to evaluate the SC performance of a selected historical period, these efforts are either an isolated effort or limited to develop their methods/models for predicting and optimizing SC performance [51–55]. As far as the authors are aware, they have not been applied in practical SC management. So it is necessary to propose and develop a model that can be used not only for evaluating but also for predicting and optimizing SC performance. In this section, the existing performance indicator systems and methods will be first discussed and evaluated in Section 5.2; various natural-inspired algorithms will be reviewed and their applications for SC performance evaluation will be discussed in Section 5.3; based on the work in Sections 5.2 and 5.3, 5DBSC and LM-BP neural network and its application in SC performance evaluation will be presented in Section 5.4 and 5.5, respectively; then, a model will be proposed using LM-BP neural network and 5DBSC for SC evaluation in Section 5.6 and a case study of SC performance evaluation of an automotive company in Changchun, Jilin, China will be discussed using the proposed model in Section 5.7.

5.2. Indicator systems and methods for SC performance evaluation

The performance evaluation is an important part of SCM. It uses a set of defined indictors for objectively or subjectively measuring their performance. The traditional indicator systems and methods were normally developed for evaluating the performance of a single enterprise [42, 56–57]. They cannot be applied to evaluate the performance of the whole SC and enterprise cooperation situations. That would eventually lead to the losses of competitive advantages of a SC as a whole.

There have been efforts made for proposing and developing various indicator systems for SC performance evaluation. Beamon proposed a method that involves the quantitative and qualitative indicators to evaluate the SC performance. The indicators included resources, output, and flexibility, in short ROF [42]. Chen Ke proposed an integrated '3+1' method for the performance evaluation of a SC. This method consists of four submethods. They are for

extracting the key indicators, analyzing factor correlation, discovering impacting-routine, and mining hidden patterns, respectively [43]. Bolch classified the performance evaluation into three parts [44]. The first part is the internal performance evaluation, and the main indicators include asset management, productivity, quality, customer service, and cost management; the second part is the external performance evaluation, and the main indicators include baseline assessment and the customer adaptations; the third part is the comprehensive performance evaluation, and the main indicators include the response time and the total cost of a SC, the ratio of on-shelf and inventory, standby time, the available days of inventory and cash-return time.

Meanwhile, the efforts have also been made to propose and develop methods for performance evaluation. Return on investment (ROI) was proposed by Dupont Company in the US and an early method for SC performance evaluation [58]. KPI is a performance evaluation method for selecting the key indicators for measuring, sampling, calculating, and analyzing. It is a tool that can be used to decompose an enterprise's strategy into operatable futuristic target [45]. KPI method is based on the assumption that people involved would take all necessary actions in order to achieve the predefined aim. SC Operations Reference (SCOR)was jointly proposed and developed by the two the US companies, PRTM and AMR. SCOR mainly consists of three layers and four components [20]. Among the three layers, the first one is the description layer. This layer describes the five fundamental business processes: planning, material acquisition, manufacturing, delivery, and reverse material-flow. The second one is the provision layer. This layer provides the enterprise own-selected key business processes. The third one is business process decomposing layer for analyzing the details of the business processes selected in the second layer. The four components include the fundamental description of the features of business processes, the general definitions of the business processes, the best practices, and choice of the software. There are 11 indicators: delivery, order fulfillment (including the customer satisfaction), order finished rate, SC response time, production flexibility, the total cost of SCM, value-added productivity, guaranteed costs, cash flow cycle, the stock turnover rate, and asset turnover days. In 1992, Kaplan and Norton first proposed Balanced Scorecard (BSC) [16]. There are four layers of the indicators: (1) accounting layer, (2) customer layer, (3) internal business process layer, and (4) learning and development layer. The characteristics of BSC are simple, straight forward, and clear in layer classification.

Benchmarking was proposed and developed by American Xerox Co. It is used for analyzing the enterprise's current situation. In benchmarking, the best practices learned from the enterprises in the same or the other industrial sectors are used as the evaluation standard to learn their the successful experiences and to catch up and surpass the successful enterprises [47]. In benchmarking method, the whole SC is considered as the integrated unit to learn the wealth of experience and success factors of the other whole SC in order to optimize and integrate their own SC.

In addition, AHP has been applied to the performance evaluation [24]. With AHP, some qualitative parameters can be expressed as the quantitative ones. AHP is a multiobjective decision method that combines both quantitative and qualitative analysis methods. The main

disadvantages of AHP are that the decision-makers' subjective opinions are overstressed, and the subjective bias is relatively big.

Among the above performance evacuation methods, BSC is widely adopted because of its simplicity, clear objective definition, and comprehensiveness. The central principle of BSC is its capability of achieving the balance between the various performance indicators. The main tasks of BSC are clarifying the strategy and reaching agreement, effectively communicating the tactics between the enterprises, linking the departmental and individual aims and annual budget, linking tactics, long-term aims and annual budget, identifying and linking tactic plans, carrying out the periodic and systematic evaluation, and postreview for learning and modifying the tactics. The four layers of the conventional BSC serve the enterprises' long-term strategy and tactics. In every layer, objectives, evaluation items, objective values, and action plans are analyzed, as shown in **Figure 8**.

There are different models of BSC. Wong applied BSC to study the performance from material flow performance, production flexibility, order indicator, and cash turnover time [60]. Akkermans et al. thought that there is a flaw of cause and effect relationships and time delay in BSC, and its variables can be either causes or results and their relationships are not linear [61]. In addition, the performance indicators in BSC do not cover the indicators that are directly related to suppliers' performance. To avoid this problem, the 5DBSC has been proposed [17]. In 5DBSC, there are five different aspects of indicators. Among them 3 are qualitative and 11 are quantitative. Performance indicators of 5DBSC are more inclusive and cover the two indicators for supplier evaluation. So in this case study, 5DBSC will be used to build the performance evaluation model of a SC. The details of the 5DBSC will be discussed in Section 5.4.

Though there have been claimed applications of the performance indicator systems and methods as discussed above, there are still quite a few issues that hinder their applications:

1. It is difficult to obtain all indicator data from every partner enterprises on the chain.

2. There are no widely accepted methods for mathematically modelling all qualitative indicators so that the indicators can be properly considered.

3. The relationships between these indicators are very complicated. Some of them are interrelated. So it is impossible to have a closed form expression to include all these 14 indicators for SC performance evaluation.

4. There are limited further developments of the methods for using these indicators for SC performance evaluation, which prevent the people in industry from applying 5DBSC. Even when 5DBSC is applied, the results are different for each times they apply.

5. Even though there are numerical methods available for processing these indicators, they are mainly used for the evaluation of the history data. They are not for predicting, simulation, and optimization purposes.

From the above discussion, it can be seen that it is important to develop new models for the people in industry to apply them for SC performance evaluation after selecting a set of the performance indicator systems. The SC performance evaluation can be expressed as:

Figure 8. BSC (source [59]).

$$[A][P_i] = [S_p] \tag{1}$$

where A is a $m \times n$ transformation matrix for mapping the n performance indicators into m SC performance evaluation index, P_i is a $n \times 1$ performance indicator vector for expressing n indicators of a selected performance system and Sp is a $m \times 1$ performance evaluation vector for expressing m performance evaluation indices. So one of the main task of SC performance evaluation is to determine A.

As discussed above, the main limitation of the current method is that it is difficult to build a closed form of matrix A in Eq. 1. However, a considerable amount of efforts have been made in applying the natural-inspired methods or algorithms for various science, engineering, and business management applications. These methods can be used to build a model for SC performance evaluation.

5.3. Natural-inspired algorithms and their applications to SCM performance evaluation [62]

5.3.1. Natural-inspired algorithms

There are a number of natural-inspired algorithms that can be used for engineering and business system analysis and optimization: Ant colony optimization (ACO) is a metaheuristic algorithm for a wide range of combinatorial optimization problems [63–64]; Bees algorithm (BA) is inspired from the food foraging behavior of honey bees and a population-based optimization algorithm for many combinatorial optimization problems[65]; Genetic algorithm (GA) generates solutions to search, optimization, and machine-learning problems via applying techniques inspired by biological evolution and GA has been widely adopted to solve complex problems, especially in the areas of scheduling, global optimization, and control engineering [66]; Firefly algorithm (FA) is inspired by the firefly's biochemical and social aspects that fireflies produce luminescent flashes as a signal system to communicate with other fireflies, especially to prey attractions [67]. If the SC performance evaluation can be expressed as a combinatorial optimization problem, then both ACO-based and BA-based algorithms can be used for SC performance evaluation including history data analysis, prediction, and optimi-

zation. Similarly, GA can also be used in the various optimization problems in SC performance evaluation.

ANN are information-processing paradigms inspired by the way biological neural systems process data. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network. In more practical terms neural networks are nonlinear statistical data modelling or decision-making tools. They can be used to model complex relationships between inputs and outputs or to find patterns in data. There have been a significant number of publications about ANN and its applications [68–70]. The application areas of ANNs include system identification and control (vehicle control and process control), game-playing and decision-making (back gammon and chess, racing), pattern recognition (radar systems, face identification, and object recognition), sequence recognition (gesture, speech, and handwritten text recognition), medical diagnosis, financial applications, data mining (or knowledge discovery in databases), visualization, and e-mail spam filtering. But as far as the authors are aware, there are very limited efforts in applying ANN in SC management. However, the previous applications of ANN provide the solid knowledge background for proposing and developing ANN-based algorithms for SCM performance analysis and optimizations.

Besides the algorithms discussed above, some other algorithms have also been reported. Evolution programming algorithm (PA) was proposed by Fogel [71]. PA is different from GA in that the evolution in GA is only between 'father' and 'son' generations, but in PA, it is stressed that the evolution can be among the same group of the creatures. Particle swarm algorithm (PSA) was proposed by J Kennedy in 1995 [72]. It mimics the food hunting behaviors of bird flock. The main characteristic of PSA is that the searching is based on the searching speed but not on the gradient information. PSA has been applied in functional optimizations, neural network training, industrial system optimization, control, etc. Immune algorithm (IA) is based on the inspiration of the biological immune system [73]. IA can be used to tackle complex problems and produce a reasonable manufacturing schedule within an acceptable time.

5.3.2. Applications of natural-inspired algorithms to SC performance evaluation

(1) The applications of genetic algorithm

Zhang et al. applied the genetic algorithm to selectively analyze the eight different aspects of the performances of a SC, including the efficiency, satisfaction, cooperation, supply, dispatching, cost, and profit. Their work was valued in the area of the complexity simplification [74]. Li carried out the study in the area of Eigenvalues selection and optimizing support vector machines (SVM, also support vector networks) in order to reduce the performance indicator number when evaluating a SC [51]. Yu proposed the SC optimization model with soft time windows-SC network (STW-SCN) and hard time window-SC network (HTW-SCN) [75].Then, GA was used to find the solution of the model. Gabbert applied GA to study the complicated transportation scheduling problem of a rail-network [76]. Liu Cheng (2006) studied the routine optimum problem of the logistics with STW-SCN [77].The transportation segment of a SC was optimized, and hence, the performance was improved.

In the performance evaluation of a SC, GA application is different from that of a neural network. In a neural network, the evaluation model is directly established, but GA is mainly used for data processing and jointly applied with the other system models. GA plays an important role in efficient data processing for the evaluation of a SC.

(2) Applications of neural network

Pawlak studied a kind of neural network with simplified parameters by combining the data mining theory of rough sets and the intelligent optimization method [78]. Shi investigated the domain, condition, and decision features of rough set theory and applied these concepts into the performance evaluation of a SC including performance indicator simplification, redundant indicator removal. He used BP network for training, and this case study has shown that the predicted result was fitted well to the practical data and the error was about 10.36% [52]. Xi investigated the application of the modified fuzzy neural network to the performance evaluation of a SC. In his study, the middle layer was divided into fuzzy layer and reasoning layer. The main achievement of his study was that the people's bias and the randomness of the evaluation process have been minimized to achieve the relatively objective results [53]. Zheng proposed a dynamic evaluation method of a SC by combining the rough set reduction technique and the learning capability of a BP neural network. His method was first implemented based on the reduced number of the performance indicators and BP neural network to learn from and train samples. The trained neural network was used for the evaluation [26]. The advantage of this method is that the data processing task is small, and hence, the complexity of BP neural network structure is simplified and the computation is reduced. However, this method's reliability is not as high as expected when also carried out as a study of evaluating the performance of the materials SC in Beijing using BP neural network [54].

(3) Applications of other algorithms

PSA is mainly applied in the areas of material scheduling, transportation, and inventory management. It is applied to optimize the results of a neural network. Xu applied the particle swarm optimization algorithm to find the solution of the collaborative optimum model of a multilayer SC from the perspective of production scheduling and group dispatching [42]. The application of Ant colony algorithm (ACA) to SCM has been focused on the scheduling and the vehicle routine optimization [79]. Li defined an ecological chain by combining SC, industry chain and value chain, and established logistic grow model for enterprises, enterprise group Lotka-Volterra predation model, and enterprise symbiosis model [80–81].

In summary, the neural network has been used in the performance evaluation of a SC. The corresponding theories, applications, and the required computer programming have been studied. The other algorithms have been tried in the SC management, but as far as the authors are aware, there have been no direct applications to the performance evaluation of a SC. The feature of GA makes it be widely applied in the data processing in the performance evaluation of a SC, but cannot be used as an independent method. The particle swarm optimum algorithm and ACA can be used for routine scheduling in the transportation and production stages of a SC, but their applications are limited in the performance evaluation of a SC. However, they

can be jointly applied with neural networks in the performance evaluation of a SC. This can be the focus of the future researches.

In a neural network, an algorithm is required for updating weight and thresholds for training the network. Back propagation (BP) algorithm was initially developed to achieve the training and then various BP-related algorithms have been developed. Compared with the existing BP algorithms, the computation amount in LMBP algorithm is increased for each iteration, but the iteration times are considerably reduced, and hence, the convergence speed is increased. LMBP is the fastest neural network training algorithm for those networks with intermediate number of parameters, even for the cases that require the large amount of computations [82–83]. For the case of SCM performance evaluation, it is impossible to have a closed form mathematical performance objective function, so it requires iterative searching. It is often that the searching does not converge when the other BP algorithms are used, which can lead to the failure of generating a reliable evaluation. In addition, to establish a reliable and meaningful model for SC performance evaluation, a large amount of historical data should be collected and used. This demands the high search speed of the algorithm. So LMBP is a better algorithm compared with the other BP algorithms. Therefore, in this case study, LMBP is selected as the natural-inspired algorithm for evaluating SC performance and will be discussed in Section 5 in details.

5.4. 5 DBSC

A 5DBSC was proposed by Zheng for the SC performance evaluation [26]. The 5DBSC includes the four groups of the indicators adopted in the conventional BSC plus a new supplier dimension. The supplier dimension includes the on time delivery and flexibility. The indicator structure of 5DBSC is shown in **Figure 9**, and the indicator system of 5DBSC is listed in **Table 3**.
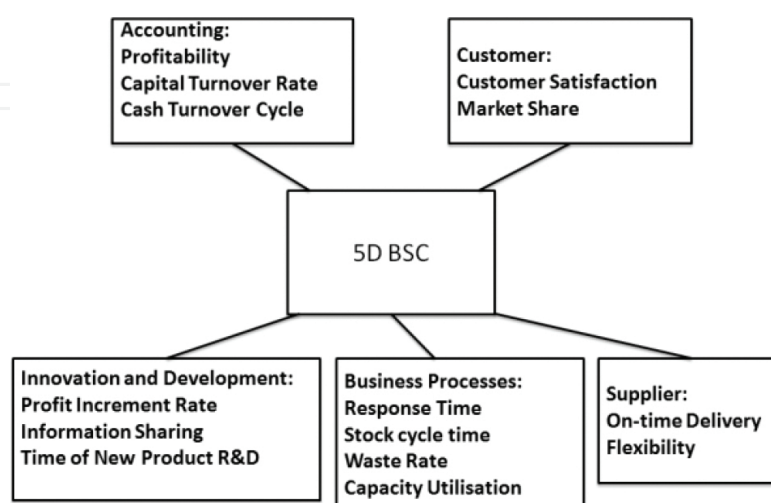

Figure 9. The indicator system of a 5D-BSC.

Indicator Groups	Indicators	Nature of indicators	Meaning of indicators
Accounting	Profitability (F_1)	Quantitative	Profit level of a SC
	Capital turnover rate (F_2)	Quantitative	Management efficiency of the net capital of a SC
	Cash turnover time (F_3)	Quantitative	Cash flow payback period
Customer	Customer Satisfaction (C_1)	Qualitative	Customers' awareness and acceptability
	Market Share (C_2)	Quantitative	Size of the customer community
Business processes	SCRT (SC response time) (P_1)	Quantitative	Required time from all enterprises on the chain finding the changes of the market requirements to absorbing these changes and adjusting their plans to meet these changes.
	Stock turnover rate (P_2)	Quantitative	Amount of cash in the stock account
	Waste rate (P_3)	Quantitative	The quality control and production technology
	Capacity utilization (P_4)	Qualitative	Facility application level
Innovation and development	Profit increment rate (D_1)	Quantitative	Development capability of an enterprise
	Information Sharing (D_2)	Qualitative	Level of the information integration Dependent on the partners strategic relationships
	Period of a new product R&D (D_3)	Quantitative	How fast a chain to respond to the market changes. Different from each products and enterprises, so it is difficult to determine its value.
Suppliers	On time delivery rate (S_1)	Quantitative	Delivery's capability of a supplier
	Flexibility (S_2)	Qualitative	SC's capability of dealing with the special business environment and meeting the customers' special requirements or unexpected requirements.

Table 3. The indicators of 5D BSC.

5.5. LMBP network algorithm and its application in SC performance evaluation

A LMBP feed-forward neural network is a neural network with LMBP algorithm for the network training (**Figure 10**).
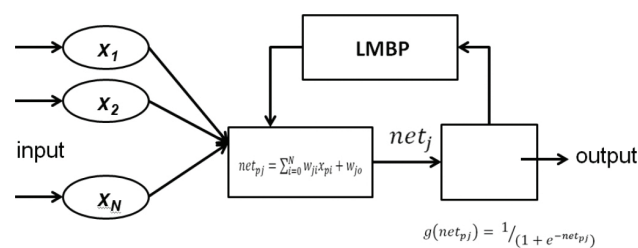
Figure 10. LMBP neural network.

In the prediction context, multilayer FNN training consists of providing input–output examples to the network and minimizing the objective function (i.e., error function) using either a first-order or a second-order optimization method. This so-called "supervised training" can be formulated as minimizing an error function of neuron weights. The error function is the sum of the nonlinear least squares between the observed and the predicted outputs, defined by Eq. 2 as follows:

$$E = \frac{1}{2} \sum_{p=1}^{N} \sum_{k=1}^{M} \left(y_{pk} - \hat{y}_{pk} \right),$$
(2)

where N is the number of the patterns and M the total output units, y represents the targeted output and $\hat{y}$ the model predicted output.

In the BP training, minimization of E is attempted using the steepest descent method and computing the gradient of the error function by applying the chain rule on the hidden layers of the FNN [84]. Consider a typical multilayer FNN whose hidden layer contains M neurons. The network is based on Eq. 3 and Eq. 4 [62]:

$$net_{pj} = \sum_{i=0}^{N} w_{ji} x_{pi} + w_{jo}$$
(3)

$$g\left(net_{pj} \right) = 1 \Big/ \left(1 + e^{-net_{pj}} \right)$$
(4)

where net_{pj} is the weighted inputs into the jth hidden unit, N the total number of input nodes, w_{ji} the weight from input unit i to the hidden unit j, x_{pi} a value of the ith input for pattern p, w_{jo} the threshold (or bias) for neuron j, and $g(net_{pj})$ the jth neuron's log-sigmoid activation function to simulate biological neuron's nonlinear characteristic. Note that the input units do not perform operation on the information but simply pass it onto the hidden nodes.

The output unit receives a net input of

$$net_{pk} = \sum_{j=0}^{M} W_{kj} g(net_{pj}) + W_{ko}$$
(5)

$$\hat{y}_{pk} = g\left(net_{pk} \right)$$
(6)

where M is the number of hidden units, W_{kj} represents the weight connecting the hidden node j to the output k, W_{ko} is the threshold value for neuron k, and $\hat{y}_{pk}$ the kth predicted output.

Recall that the ultimate goal of the network training is to find the set of weights W_{ji} connecting the input units i to the hidden units j and W_{kj} connecting the hidden units j to output k, that minimize the objective function (Eq. 2). Since Eq. 2 is not an explicit function of the weight in the hidden layer, the first partial derivatives of E are evaluated with respect to the weights using the chain rule, and the weights are moved in the steepest-descent direction. This can be represented mathematically as

$$\Delta W_{kj} = -\eta \, \partial E \big/ \partial W_{kj} \tag{7}$$

where η is the learning rate which simply scales the step size. The usual approach in BP training consists in choosing η according to the relation $0 < \eta < 1$. From Eq. 7 it is straightforward that BP can suffer from the inherent slowness and the local search nature of first-order optimization method [62].

However, second-order nonlinear optimization techniques are usually faster and more reliable than any BP variants [85]. So LMBP was developed for multilayer FNN training. The LMBP uses the approximate Hessian matrix (second derivatives of E) in the weight update procedure as follows:

$$\Delta W_{kj} = -\left[H + \mu I\right]^{-1} J^T e \tag{8}$$

where e is the residual error vector, μ a variable small scalar which controls the learning process, $J = \nabla E$ is the Jacobian matrix, and $H = J^T J$ denotes the approximate Hessian matrix usually written as $\nabla E \cong 2 \, J^T J$. In practice, LMBP is faster and can be used to find better optima for a variety of problems than do the other usual methods [62].

After processing all of the layers, the activated result, y, of the output layer, compared with the target value $\hat{y}$, and the resulted error will be propagated backward to the network's weight to minimize the overall error.

The standard LMBP training process can be described in the pseudo-code as follows:

1. Initialise the weights and parameter μ ($\mu = 0.01$ is normally appropriate).

2. Compute the sum of the squared errors over all inputs, $E(w) = e^T e$, where W= [consists of all weights of the network, e is the error vector comprising the error for all the training nodes.

3. Solve Eq. 5 to obtain the increment of weight $\Delta w = -[J^T J + \mu I]^{-1} J^T e$, where J is the Jacobian matrix, μ is the learning rate which is to be updated using the decay rate, β depending on the outcome. In particular, μ is multiplied by β ($0 < \beta < 1$).

4. Recomputed the sum of squared errors $E(w)$.

Using $w + \Delta w \, \Delta w$ as the trial W, and judge

IF trial $E(w)<$ in step 2 then

$w = w + \Delta w$; $\mu = \mu \cdot \beta$ ($\beta = 0.1$); go back to step 2

ELSE

$\mu = \mu/\beta$; go back to step 4

END IF

5.6. A model for performance evaluation of a SC

In this section, a model for performance evaluation of a SC is proposed. This model is based on 5DBSC and LMPB neural network as shown in **Figure 11**.
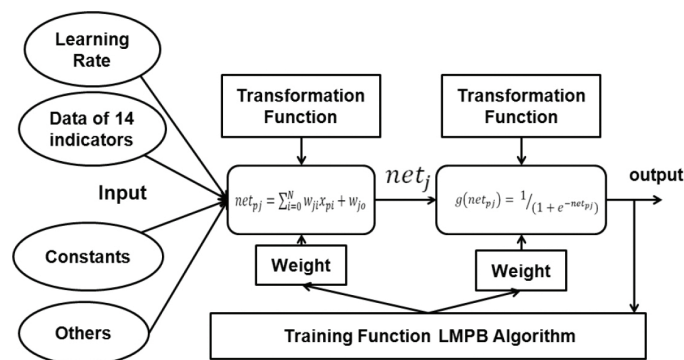
Figure 11. LMBP neural network for evaluating the performance of a SC.

The procedure of proposed model is shown in **Figure 12**. There are three stages in the model: Stage 1—data preparation, Stage 2–training neural network using LMBP algorithm, and Stage 3—postprocessing and application.

In Stage 1, there are three tasks (1) collect the data of the 14 indicators of 5DBSC for a period, (2) applying a technique for data preprocessing, here the main work is to normalize the collected data of the 14 indicators and (3) variable data selection.

In Stage 2, the task is to follow the steps and apply equations in Section 4 to train the neural network as shown in **Figure 11**.

In Stage 3, there are two tasks: (1) postprocess the outcome, mainly record the weights, and thresholds of the trained neural network and (2) apply the model to evaluate, analyse, and optimize the performance of a SC.

5.7. Case study—result analysis

Matlab and its neural network tool box have been used to implement the proposed model in Section 6. An automotive company in Changchun, Jilin Province, China, was selected as the case study to demonstrate the proposed model. Considering the confidential issues, the real name of the company is not used. So in this case study, this company is called Company Y. To
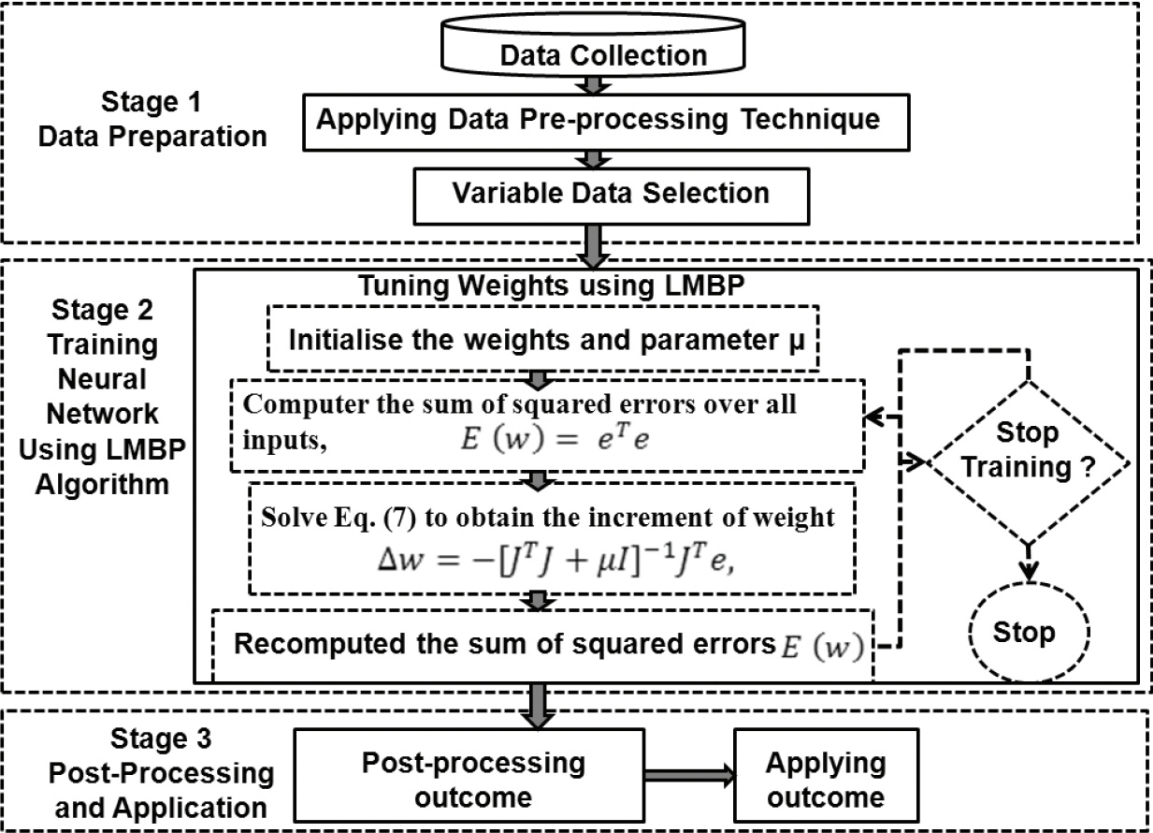
Figure 12. Procedure of the proposed model.

express the performance of a SC, a performance index system is used. There are four levels of performances: poor, reasonable, good, and excellent. These four levels are represented using a four-element vector(1 0 0 0)、 (0 10 0)、 (0 01 0)、 (0 0 0 1), respectively. The advantage of using a four-element vector over a single digit is that four-element vector can be used to express the performance between those four levels. This is especially useful for SC performance prediction and optimization.

5.7.1. Data Preparation

1) Data collection

Table 2 lists the collected data of the 14 indicators of 5DBSC of Company Y for 12 months from January to December 2012.

2) Data preprocessing

The indicators in **Table 4** have different dimensions. They should be preprocessed to be dimensionless before they can be input into LMBP network. The dimensionless process is typically to normalize the indicators' values. It is a process to remove the effects of dimensions through mathematical transformation. The range of normalized indicators' value should be [0, 1]. The normal dimensionless process method includes linear function normalization, logarithmic function normalization, and inverse cotangent function normalization. In this case

study, the linear function normalization is adopted for dimensionless processing. There are two types of indicators: the benefit type and cost type. The benefit type means that the bigger the value of the indicators, the better. In contrast, the cost type means that the smaller the value of the indicators, the better. Among these 14 indicators, C_1, C_2, F_1, P_4, D_1, D_2, S_1, and S_2 belong to the benefit type of indicators. The others belong to the cost type of indicators. The formula of the linear function normalization is either $y_i = (x_i - x_{min})/(x_{max} - x_{min})$ for the benefit type of indicators and $y_i = (x_{max} - x_i)/(x_{max} - x_{min})$ for the cost type of indicators, where x_i is the original value of the indicators before the normalization, y_i is the value after normalization, x_{max} and x_{min} are the maximum and minimum values, respectively. To determine x_{max} and x_{min}, these 14 indicators should also be classified into two different kinds: qualitative and quantitative. C_1, P_4, D_2, and S_2 are the qualitative indicators. The others are the quantitative indicators. For those qualitative types of indicators, they have to be digitized for the further processing. In this paper, 0, 1, 2, 3, and 4 are used to express poor, reasonable, good, and excellent performance of these four qualitative indicators. So their x_{max} and x_{min} are 4 and 0, respectively. For those quantitative type of indicators, the x_{max} and are determined based on the company's experiences and their meanings. The values of them are listed in **Table 5**. Then, normalized data are calculated and listed in **Table 6**.

	Customer dimension		Accounting dimension			Internal business process dimension				Innovation and development dimension			Supplier dimension		SC performance
C_1	C_2	F_1	F_2	F_3	P_1	P_2	P_3	P_4	D_1	D_2	D_3	S_1	S_2		
Jan.	4	1.54%	0.444	0.263	120	90	0.25	0	4	0.000	3	200	1	2	reasonable
Feb.	4	1.29%	0.426	0.225	130	91	0.10	0	4	−0.171	3	200	1	3	poor
Mar.	3	1.59%	0.520	0.328	130	88	0.30	0	4	0.660	3	120	1	3	good
Apr.	4	1.64%	0.507	0.310	120	89	0.30	0	4	−0.069	4	140	1	3	good
May	4	1.29%	0.561	0.248	120	90	0.15	0	4	−0.160	4	200	1	4	reasonable
Jun.	3	1.18%	0.414	0.216	120	92	0.10	0	4	−0.281	4	200	1	4	poor
Jul.	3	1.40%	0.426	0.247	110	90	0.25	0	4	0.157	3	120	1	3	reasonable
Aug.	4	1.39%	0.459	0.275	110	90	0.25	0	4	0.136	3	130	1	4	good
Sep.	3	1.44%	0.468	0.295	110	90	0.20	0	4	0.088	4	130	1	4	good
Oct.	4	1.20%	0.419	0.215	120	92	0.15	0	4	−0.324	4	180	1	4	poor
Nov.	4	1.62%	0.500	0.289	120	88	0.30	0	4	0.489	4	120	1	4	excellent
Dec.	4	1.64%	0.509	0.322	120	90	0.25	0	4	0.095	4	120	1	4	excellent

Table 4. The original data of the supply chain of Y Company in 12 months (2012).

C_2	F_1	F_2	F_3	P_1	P_2	P_3	D_1	D_3	S_1
(0, 2%)	(0, 1)	(0, 1)	(100,150)	(85,95)	(0, 1)	(0, 1)	(0, 1)	(100,210)	(0, 1)

Table 5. The values of x_{max} and x_{min} of the quantitative indicators.

	C_1	C_2	F_1	F_2	F_3	P_1	P_2	P_3	P_4	D_1	D_2	D_3	S_1	S_2	SCM performance
Jan.	1.00	0.77	0.44	0.26	0.60	0.50	0.25	1.00	1.00	0.00	0.75	0.08	1.00	0.50	(0 1 0 0)
Feb.	1.00	0.65	0.43	0.23	0.40	0.40	0.10	1.00	1.00	−0.17	0.75	0.08	1.00	0.75	(1 0 0 0)
Mar.	0.75	0.80	0.52	0.33	0.40	0.70	0.30	1.00	1.00	0.66	0.75	0.75	1.00	0.75	(0 0 1 0)
Apr.	1.00	0.82	0.51	0.31	0.60	0.60	0.30	1.00	1.00	−0.07	1.00	0.58	1.00	0.75	(0 0 1 0)
May.	1.00	0.65	0.56	0.25	0.60	0.50	0.15	1.00	1.00	−0.16	1.00	0.08	1.00	1.00	(0 1 0 0)
June.	0.75	0.59	0.41	0.22	0.60	0.30	0.10	1.00	1.00	−0.28	1.00	0.08	1.00	1.00	(1 0 0 0)
July.	0.75	0.70	0.43	0.25	0.80	0.50	0.25	1.00	1.00	0.16	0.75	0.75	1.00	0.75	(0 1 0 0)
Aus.	1.00	0.70	0.46	0.28	0.80	0.50	0.25	1.00	1.00	0.14	0.75	0.67	1.00	1.00	(0 0 1 0)
Sep.	0.75	0.72	0.47	0.30	0.80	0.50	0.20	1.00	1.00	0.09	1.00	0.67	1.00	1.00	(0 0 1 0)
Oct.	1.00	0.60	0.42	0.22	0.60	0.30	0.15	1.00	1.00	−0.32	1.00	0.25	1.00	1.00	(1 0 0 0)
Nov.	1.00	0.81	0.50	0.29	0.60	0.70	0.30	1.00	1.00	0.49	1.00	0.75	1.00	1.00	(0 0 0 1)
Dec.	1.00	0.82	0.51	0.32	0.60	0.50	0.25	1.00	1.00	0.10	1.00	0.75	1.00	1.00	(0 0 0 1)

Table 6. The processed data of Company Y's supply chain in 12 months.

5.7.2. Determination of the number of nodes in hidden layer

The determination of the number of hidden layers and their nodes are the focuses of a LMBP network analysis. According to universal approximation theory, as long as there are enough nerve cells in the hidden layer, a LMBP network can be used to approximate any functions. It only requires the two hidden layers when learning noncontinuous functions. In practical applications, it is normal to test the case with one hidden layer, then to see if it is required to use the two hidden layers. In this case study, one hidden layer is chosen for the test.

The node numbers of the input and output layers are determined by the sample characteristics, sample number, and sample's experimental objective number. The sample data are represented with the SC performance indicators and four-dimensional data used for the four levels of the SC performance in 12 months. So there are 14 nodes in the input layer and 4 nodes in the output layer. The number of nodes in the hidden layer has the significant impact on the structure and characteristics of a network. The unnecessary high number of nodes in the hidden layer would reduce the learning and reasoning efficiency, but the low number of the nodes would lead to the nonconvergence of learning. The trial-and-error method is currently widely used [46].

In this case study, the initials have been set to zero, then to try to adjust the node numbers of the LMBP network for comparing the errors. The results of running our Matlab program have been listed in **Table 7**. From the table, it can be seen that the value of MSE is the minimum at 5.13E-09 when the node number of hidden layer is 18.

Nodal No. in Hidden Layer	8	10	12	14	16	**18**	20	22	24	26
Epoch	12	4	4	3	4	**3**	3	4	4	5
MSE(10^{-6})	3.57	0.346	0.467	2.40	0.155	**0.005**	7.69	4.09	1.99	98

Table 7. The impact of the node number of the hidden layer on the LMBP network.

5.7.3. *The determination of transformation functions*

The transformation functions in the neural cells include logarithmic function (Logsig), tangent function (Tansig), and linear function (Purelin). Purelin is a transformation function that is inputted through input layer to calculate the outputs of the output layer. This function can be used to transfer the inputs of the neural cells to the outputs through the adjusting the threshold. Tansig is a hyperbolic tangent S-type transfer function. It can be used for mapping the neurons' outputs into [–1,1]. Logsig is a logarithmic S-type transfer function. It is used for mapping the neurons' outputs into [0,1]. These three functions are differentiable and suitable to train a LMBP algorithm neural network. K.M. Hornik thought that as long as there are enough nodes in the hidden layer, employing S-type functions in the hidden layer of a three-layer network, and employing linear functions in the output layer, the neural network can approximate any functions with any errors at considerably high probability [86]. But it is not easy to meet the preconditions.

In this case study, numerous trial experiments have been repeated. From the experimental results, it has been found that the errors of our neural network are minimal if Purelin functions are employed for both from the input layer to the hidden layer and from the hidden layer to the output layer. The results have been listed in **Table 8**.

	t–t	t–l	t–p	p–t	p–l	p–p	l–t	l–l	l–p
Epoch	11	9	4	22	8	**3**	11	18	4
MSE	4.89E-04	4.50E-04	1.13E-04	9.72E-04	5.20E-04	**5.13E-09**	2.04E-04	7.24E-04	2.94E-06

*t is for Tansig function, p is for Purelin function, and l is for Logsig function.

Table 8. The error comparison analysis when employing the different transformation.

The BP neural network toolbox of Matlab 7.6 provides the LMBP training functions, it is called Trainlm. The format of trainlm function is as [w, b, te, tr]=trainlm[$w, b, 'f', x, t, tp$], where: p is the input vector matrix, t is the target vector, w is the new weight, b is the new threshold vector, f is the transformation functions between the layers of the network, te is the actual network

training times, *tr* is error squared sum vector of the network, and *tp* is the optional parameters. In our program, *tp* is set as the maximum training time.

The learning speed predetermines the rates of modification of the weight and the threshold. When the learning speed is low, the weight of a network is relatively quick to converge, but the learning time can be long. It is normal to set the learning speed to 0.01. In this case study, the training parameters have been set as follows: net.trainParam.show = 5; net.trainParam.lr = 0.01; net.trainParam.mc = 0.9; net.trainParam.epochs = 1000 and net.trainParam.goal = 1e-3.

5.7.4. Analysis of the training results

The last column of **Table 4** is used for representing the performance evaluation of Company Y for 12 months in 2012. They can be rearranged as

$$To = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{10}$$

As discussed above, the parameters of Company Y's LMBP neural network are the node number of the input layer is 14, that of the hidden layer is 18, that of the output layer is 4, the transformation function is purelin, training function is trainlm, the iteration number is 3, and the criterion mean square error (MSE) was e-03. So the program should be compiled as net = newff(P, T_0, 3, {'purelin', 'purelin'}, 'trainlm', 'MSE'), where P is a 12 by 14 matrix of 14 indicators in the period of 12 months.

The results of the LMBP network program for the case study are as follows: when the LMBP network reached the stable condition, MSE was 5.13E–09 and the fitness of the network training, R was approximately 1. The results of performance evaluation of company's SC for the 12 months in 2012 are

$$Tc = \begin{bmatrix} -0.0001 & \mathbf{0.9999} & -0.0001 & -0.0001 & -0.0001 & \mathbf{0.9999} & -0.0001 & -0.0001 & -0.0001 & \mathbf{0.9999} & -0.0001 & -0.0001 \\ \mathbf{1.0000} & -0.0000 & -0.0000 & -0.0000 & \mathbf{1.0000} & -0.0000 & \mathbf{1.0000} & -0.0000 & -0.0000 & -0.0000 & -0.0000 & -0.0000 \\ 0.0000 & 0.0000 & \mathbf{1.00001.0000} & 0.0000 & 0.0000 & 0.0000 & \mathbf{1.00001.0000} & 0.0000 & 0.0001 & 0.0001 \\ 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & 0.0001 & \mathbf{1.00011.000\ 1} \end{bmatrix} \tag{11}$$

where each column stands for performance index vector for one month.

The difference between *To* and *Tc* is

$$dT = 10^{-3} \begin{bmatrix} 0.065 & 0.070 & 0.092 & 0.088 & 0.081 & 0.070 & 0.074 & 0.089 & 0.086 & 0.081 & 0.104 & 0.105 \\ 0.005 & 0.003 & 0.011 & 0.008 & 0.003 & 0.002 & 0.008 & 0.007 & 0.007 & 0.002 & 0.010 & 0.008 \\ -0.031 & -0.032 & -0.046 & -0.046 & -0.038 & -0.032 & -0.038 & -0.043 & -0.042 & -0.036 & -0.052 & -0.051 \\ -0.083 & -0.082 & -0.127 & -0.121 & -0.093 & -0.078 & -0.102 & -0.113 & -0.111 & -0.089 & -0.138 & -0.133 \end{bmatrix} \tag{12}$$

From *dT*, it can be seen that the model using 5DBSC and LMBP neural network for SC performance evaluation is accurate. The maximum error is less than 0.02%, well lower than 10% accepted in SC performance evaluation. That means that the model is accurate, valid, and efficient.

5.7.5. Optimizing the SC performance of Company Y

From **Table 4**, it can be seen that the SC performance of Company Y for the period of February, June, and October, 2012 was evaluated as poor (1 0 0 0). In this section, the data in these three months will be used as an example to demonstrate how the developed model can be used to optimize SC performance of these months.

The method adopted in this case study is to use an excellent performance month as the benchmark month. It can be seen that the performance was evaluated as excellent for November and December. So one simple way is to adjust the poor performance's14 indicators toward excellent performance's 14 indicators, respectively. In this case study, a linear equation is adopted for adjusting data and expressed as Eq. 9.

$$x_{ap} = x_{ip} + \lambda(x_{ep} - x_{ip}) \tag{9}$$

where x_{ap} is the adjusted indicator, x_{ip} is the poor month's indicator, x_{ep} is the excellent month's indicator, and λ is the adjusting factor with the value range from 0 to 1. **Table 7** lists the numerical results that shows how the performance is improved when February's data is adjusted toward November's data. From the **Table 9**, it can be found that

When $\lambda = 0$, that means that the data of 14 indicators are not changed, so the performance vector remains the same and the performance is classified as poor.

When $\lambda = 0.25$, that means that the data of 14 indicators are changed 25% toward those values of the excellent month's 14 indicator, the performance vector is changed to [0.75 0 0 0.25], which means that the performance is improved 25%, similarly. When $\lambda = 0.5$ and 0.75, the performance is improved 50% and 75%, respectively. The same results have been achieved when all three poor months' indicators are adjusted toward those of the two excellent months' indicators. The reason behind it is that the new model is developed using the linear transformation functions for both from the input layer to the hidden layer and from the hidden layer to the output layer. This is the main advantage of the proposed model over the other models. Again, this proves that the new model is valid and reliable and can be used to optimize SC performance.

It should be pointed out that, in this example, the values of all the 14 indicators are adjusted toward the excellent month's values at the same rate. Though this does not affect the validity and reliability of the new model, it would be very difficult or practically impossible to implement this kind of indicator changes.

Further work should be carried out to establish a cost model that should include the costs for any changes of any of 14 indicators and the benefits gained from the changes.

The optimization function of the model not only provides the people a tool to improve the performance of a SC but also guides the people to improve the ways they mange the SC activities. In this numerical example, to achieve a 75% performance improvement, one of the changes of the indicators is SC response time (SCRT) (P_1)should be reduced from 91 days to 88.75 days. That means that Company Y should collaborate with its partners to make efforts to achieve this target. The same analysis can be done for the other indicators.

λ	C_1	C_2	F_1	F_2	F_3	P_1	P_2	P_3	P_4	D_1	D_2	D_3	S_1	S_2	New Performance
0	1	.645	.426	.225	.4	.4	.1	1	1	−.171	.75	.083	1	.75	[1 0 0 0]
.25	1	.686	.445	.241	.45	.475	.15	1	1	−.006	.813	.25	1	.813	[0.75 0 0 0.25]
.5	1	.728	.463	.257	.5	.55	.2	1	1	.159	.875	.417	1	.875	[0.5 0 0 0.5]
.75	1	.769	.482	.273	.55	.625	.25	1	1	.324	.938	.583	1	.938	[0.25 0 0 0.75]

Table 9. Performance improvement when February's data is adjusted toward November's data.

5.8. Discussion

In this case study, the existing performance indicator systems and methods have been discussed and evaluated, various natural-inspired algorithms have been reviewed, and their applications for SC performance evaluation has also been discussed. Then, a model has been proposed and developed using 5 dimensional balanced scorecard (5DBSC) and Levenberg–Marquardt Back-propagation (LMBP) neural networkfor SC performance evaluation.

A program has been written using Matlab tool box to implement the model based on the practical values of the 14 indicators of 5DBSC of a given previous period. This model can be used to evaluate, predict, and optimize the performance of a SC. The analysis results of a case study company show that the proposed model is valid, reliable, and effective. The convergence speed is faster than the previous work.

However, it should be pointed out that the focus of this paper is placed on the proposition of the new model. The development of the model was only based on a relatively short period of 12 months of Company Y. To make the model more reliable and with higher practical values, more data should be collected over longer period for training the network.

To apply the proposed model for optimizing SC performances and hence guiding companies to improve their SC management, cost model should be built as a conditional function to make sure any changes in SC management are cost effective.

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