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Chapter 1

Multi-Criteria Decision-Making Methods Application in Supply Chain Management: A Systematic Literature Review

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Additional information is available at the end of the chapter

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Abstract

Over the last decade, a large number of research papers, certified courses, professional development programs and scientific conferences have addressed supply chain management (SCM), thereby attesting to its significance and importance. SCM is a multi-criteria decision-making (MCDM) problem because throughout its process, different criteria related to each supply chain (SC) activity and their associated sub-criteria must be considered. Often, these criteria are conflicting in nature. For their part, MCDM methods have also attracted significant attention among researchers and practitioners in the field of SCM. The aim of this chapter is to conduct a systematic literature review of published articles in the application of MCDM methods in SCM decisions at the strategic, tactical and operational levels. This chapter considers major SC activities such as supplier selection, manufacturing, warehousing and logistics. A total of 140 published articles (from 2005 to 2017) were studied and categorized, and gaps in the literature were identified. This chapter is useful for academic researchers, decision makers and experts to whom it will provide a better understanding of the application of MCDM methods in SCM, at various levels of the decision-making process, and establish guidelines for selecting an appropriate MCDM method for managing SC activities.

Keywords: SCM, MCDM, strategic, tactical and operational decision-making, fuzzy, AHP/ANP, TOPSIS, systematic literature review

1. Introduction

Supply chain management (SCM) is crucial in today's competitive environment and is steadily gaining serious research attention. Companies are facing challenges in discovering ways to fulfill ever-rising customer expectations and remain competitive in the market while keeping costs manageable. To that end, they must carry out investigations to isolate inefficiencies in their supply chain (SC) processes. If a company is buying raw materials for use in manufacturing a product, which it then sells to customers that mean the organization has an SC, which it must then manage. According to [1], SCM is:

"A set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements."

SCM involves managing a series of activities relating to the planning, coordination and control of the movement of materials, parts and products from suppliers; the management of inventories of procured parts and of issues relating to production; an appropriate and cost-effective storage of products, and finally, transportation to the customer.

Another approach defines SCM in terms of different decision-making (DM) levels, namely, strategic, tactical and operational, and indicates that these DM levels of all scales optimize SC performance. On the other hand, traditional SC can be defined as a network which consists of suppliers, manufacturing facilities, distribution centers from which we procure raw materials, converted into finished good and deliver it to end user [2].

Certain differences exist between SCM and traditional logistics. Traditional logistics consists of actions that usually occur inside single organization boundaries, while SCM essentially defines a network of different companies working in coordination, with their main goal being to deliver finished products to customers. In addition, traditional logistics emphasizes SC functions, including purchasing, distribution and inventory management. SCM includes all the components of traditional logistics, but also tags on actions such as new product development, finance, marketing and customer service [3]. In this chapter, we consider following SC functions as mentioned in **Figure 1**.

1.1. Decision-making in SCM

An organization's strategic, tactical and operational decision-making plays a vital role in ensuring that its SC is operating efficiently, allowing it to achieve the highest levels of customer satisfaction at an optimum cost. Decision-making at each level should focus on gaining a competitive edge

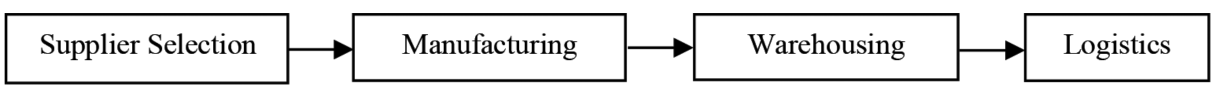

Figure 1. Considered SC functions.

and increasing market share. At each level, the nature of decision-making as well as and the related activities are different. There are three levels of decision-making which are (1) strategic-level decisions that have a long-lasting effect on the firm such as decisions related to warehouse location, capacity of warehouse and distribution centers, (2) tactical-level decisions that include decisions for the coming year such as decisions related to production, inventory level, absorption of uncertainty in production plan, transportation, and so on and (3) operational decisions that include decisions which are usually day-to-day such as loading/unloading, daily production plan, and so on.

1.2. MCDM methods and SCM

MCDM is a technique that combines alternative's performance across numerous, contradicting, qualitative and/or quantitative criteria and results in a solution requiring a consensus [4, 5]. Knowledge garnered from many fields, including behavioral decision theory, computer technology, economics, information systems and mathematics is used. Since the 1960s, many MCDM techniques and approaches have been developed, proposed and implemented successfully in many application areas [6, 7]. The objective of MCDM is not to suggest the best decision, but to aid decision makers in selecting shortlisted alternatives or a single alternative that fulfils their requirements and is in line with their preferences [8–10] mentioned that at early stages, knowledge of MCDM methods and an appropriate understanding of the perspectives of DM themselves (players who are involved in decision process) are essential for efficient and effective DM.

There are several MCDM methods available such as the analytical hierarchal process (AHP), the analytical network process (ANP), TOPSIS, data envelopment analysis (DEA) and fuzzy decision-making. MCDM has been one of the fastest growing problem areas in many disciplines [11]. Over the past decade, many researchers have applied these methods in the field of industrial engineering, particularly in SCM, in making decisions. All the methods are equally capable of making decisions under uncertainty, and each one has its own advantages.

SCM is an MCDM problem because in the entire SC cycle, we must consider different criteria related to each sub-criterion of the SC cycle. In order to manage the entire SC, we have to identify the relationship of each criterion, which in turn impacts the performance of the SC. Based on the indicators identified, we then make decisions. This shows that decision-making is critical in managing the SC cycle, and that SCM is an MCDM problem. Supply chain management decisions are made under the conflicting criteria of maximizing profit and customer responsiveness while minimizing SC risk. Multiple criteria decision-making in supply chain management provides a comprehensive overview of multi-criteria optimization models and methods that can be used in SC decision-making [12].

1.3. Objective of the study

The objective of this study is to provide a systematic literature review on the application of MCDM methods in the decision process related to the considered SC functions (supplier selection, manufacturing, warehousing and logistics). The literature will be also categorized in terms of decision-making level (strategic, tactical and operational) and sector/application area during the decision process. This study is an attempt to answer the following research questions:

a. What is the (%) distribution of MCDM methods applications in terms of different SC decision levels (strategic, tactical and operational) and in the SC functions considered?

b. What is the (%) distribution of MCDM methods applications in terms of area of application?

c. What are the top MCDM methods applied at each SC functions considered and at different SC decision levels (strategic, tactical and operational).

2. Research methodology

In order to systematically carry out our literature review and use content analysis in the process, we adopt a methodology composed of four steps, based on the practical guidelines provided by Seuring & Gold [13] and Seuring et al. [14]. The process model consists of following steps as mentioned in **Figure 2**.

Step 1: The scope of the literature review in this chapter is limited to academic reviewed journals, conference papers and graduate dissertations because of their academic relevance, accessibility and ease of search. We did not include unpublished works, non-reviewed papers, working papers and book chapters. Inclusion of such papers is suggested as a future extension of our work. Papers using only MCDM methods and its integration with MODM methods were also included. However, papers focused solely on applied MODM methods were not included because it is beyond the scope and objective of this study. We searched within titles and abstracts in the Emerald, Elsevier, Taylor & Francis, Springer and Inderscience databases. Keywords that we used are "SCM and MCDM"; "Strategic and SCM"; "Tactical and SCM"; "Operational and SCM"; "MCDM and Supplier selection"; "MCDM and manufacturing"; "MCDM and warehousing"; "MCDM and logistics"; "DM and Supplier Selection"; "DM and Manufacturing"; "DM and Warehousing"; "DM and Logistics"; and so on. We used non-method-specific and method-specific MCDM keywords, DM keywords and SCM keywords. The material selection process led to samples of 140 papers published in more than 80 journals (the complete reference list is presented in a separate reference list).

Step 2: As recommended by [13], descriptive analysis must contain the distribution of selected reviewed articles in terms of time period, papers per country and across journals. Therefore, **Figure 3** shows the annual distribution of selected articles across the period of study (2005–2017), **Figure 4** shows the top five journals and **Figure 5** shows distribution of articles published per country.

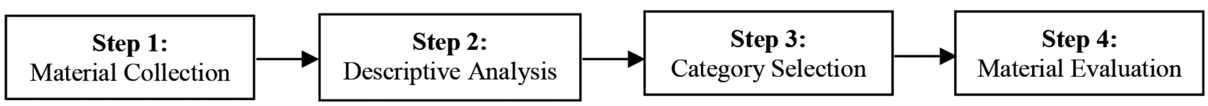

Figure 2. Literature review methodology.

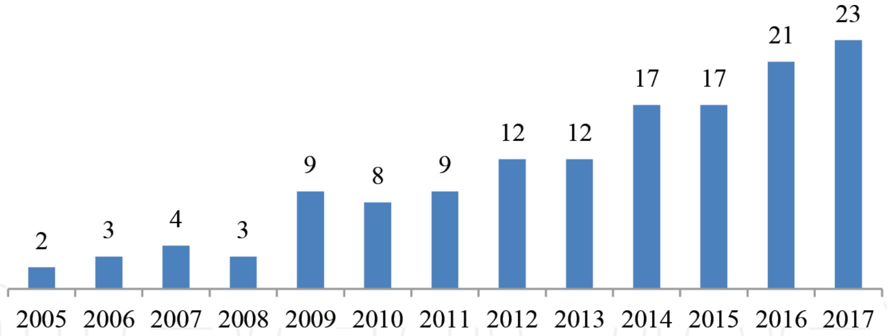

Figure 3. Annual distribution of selected articles across the period of study (2005–2017).

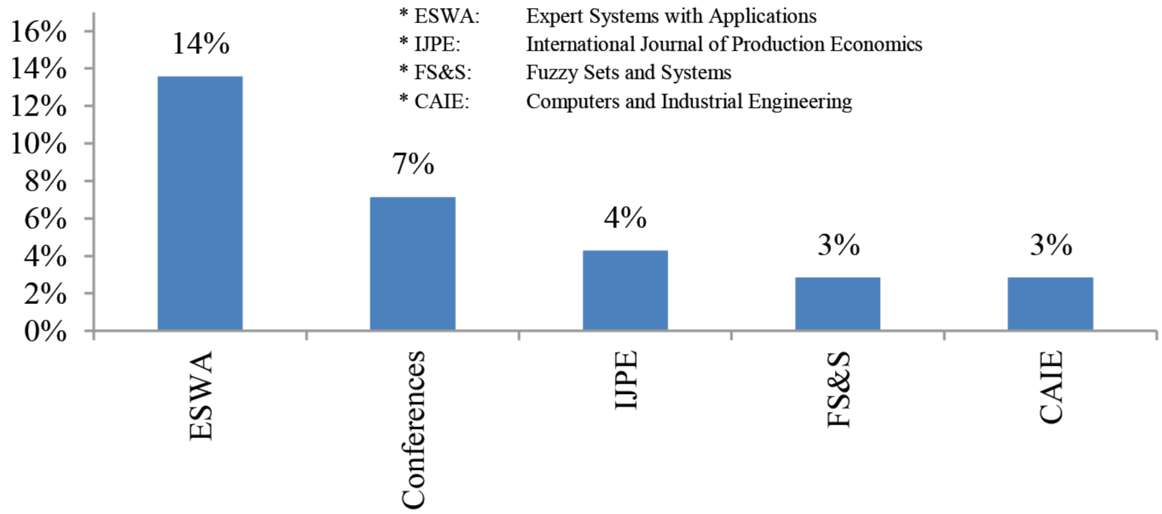

Figure 4. Top four journals of selected reviewed articles.

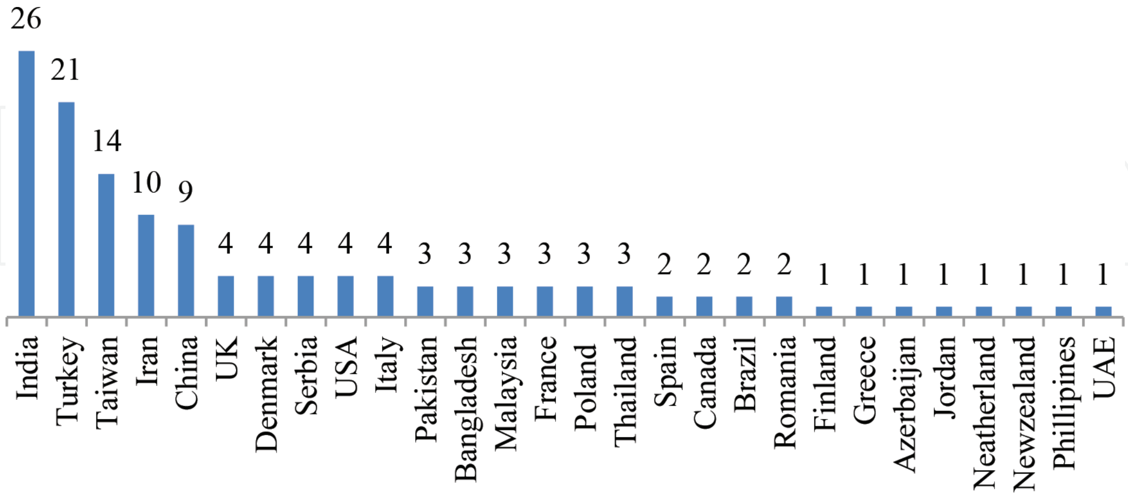

Figure 5. Distribution of articles published per country.

Step 3: Category selection is the most important and essential step of any literature review paper. Category selection developed in this chapter is in line with the objectives set in Section 1.3 and will be able to answer research questions set in the last section. Therefore, in this chapter, we categorized papers in terms of decision-making level, SC functions considered, MCDM methods used and application area. In this step, each author assigned each paper to the specific category. Distribution of papers according to the DM level is aligned with the DM level explained in the abovementioned section, while the SC functions distribution is in line with the standard SC functions definition. Other dimensions, such as the application area and methods applied, were identified by reading the abstract, and in some cases, the conclusion of the article.

Step 4: Once the category selection has been developed, categories' definitions have been clarified, and the papers were reviewed and categorized accordingly. We developed decision rules, and all authors were agreed on developed rules. All papers were read and categorized by individual reviewer, and all authors came up with the same distribution of articles. Only 11% of the papers had differences which were resolved by discussion. We paid attention to ensure the quality, reliability and validity of the review.

In the discussion given in the following section, we first show qualitative results and then proceed with a quantitative analysis.

3. Qualitative results

In this section, a systematic review of the literature on the application of MCDM methods will be discussed. We divided the literature review into the functions of SCM considered; decision-making level, sectors/application area, and country. Category selection of any literature review paper is critical to select paper and accept or reject them based on inclusion or exclusion principles.

3.1. Supplier selection

Many authors have used different MCDM methods to select suppliers strategically for different purposes and in different applications such as the best supplier selection based on sustainability principles, to integrate information on supplier behavior in a fuzzy environment, to solve the supplier evaluation problem in companies with bulk production costs associated with raw materials, and so on. At the tactical level, supplier selection involves the administration of procurement activities such as multi-product supplier selection problem, factors affecting the supplier selection process, and so on. At the operational level, supplier selection usually involves one-time procurement due to unavoidable factors. At this level of decision-making, a small quantity of a product is usually procured from a supplier to run the production line. **Table 1** shows the categorization of papers in terms of decision-making level, MCDM methods used, application area/sector and country in supplier selection.

3.2. Manufacturing

Strategically, decision-making associated with manufacturing involves capacity constraints, manufacturing process selection, and make-or-buy decisions, development of a structural model

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Papers	MCDM methods used	Sector/application area	DM level			Country
			Strategic	Tactical	Operation	
[15]	FAHP	SME	●			Thailand
[16]	FTOPSIS	General	●			Tunisia
[17]	FTOPSIS	Fertilizer industry	●			India
[18]	AHP and VIKOR	Automotive	●			India
[19]	Fuzzy- Grey Theory	Steel industry	●			China
[20]	Fuzzy Systems	General	●			China
[21]	FAHP	Railway operations		●		Brazil
[22]	FAHP	Manufacturing industry	●			Italy
[23]	AHP-QFD	Automotive	●			Pakistan
[24]	AHP -TOPSIS	General		●		India
[25]	AHP	Automotive			●	India
[26]	AHP	Automotive		●		Pakistan
[27]	AHP-TOPSIS	IT industry			●	Morocco
[28]	Electre III	Packaging industry				Romania
[29]	Fuzzy	Agri food industry			●	Iran
[30]	Fuzzy Systems	Gear manufacturing	●			China
[31]	Fuzzy-QFD	Hospital	●			Turkey
[32]	Fuzzy multi-objective	General		●		USA
[33]	Fuzzy Axiomatic Design	Plastic material manufacturer	●			Denmark
[34]	FAHP	Airline		●		Netherlands
[35]	FANP	Automotive		●		Malaysia
[36]	FTOPSIS	Energy	●			Turkey
[37]	FTOPSIS	Automotive	●			Iran
[38]	FAHP	Publishing company			●	Iran
[39]	FTOPSIS and MILP	Air filter manufacturing		●		Turkey
[40]	FTOPSIS	Detergent manufacturing		●		Iran
[41]	FAHP	General	●			Turkey
[42]	Fuzzy-MISO	Fiber manufacturing	●			India
[43]	FAHP and Fuzzy Objective LP	Garment manufacturing			●	India
[44]	FAHP	General	●			India
[45]	FAHP	Washing machine manufacturing			●	Turkey
[46]	FTOPSIS and MCGP	Watch manufacturing	●			Taiwan
[47]	TOPSIS	General	●			Italy
[48]	FAHP	Steel	●			Greece

Papers	MCDM methods used	Sector/application area	DM level			Country
			Strategic	Tactical	Operation	
[49]	FAHP	Manufacturer of medical Consumables	●			Taiwan
[50]	FTOPSIS	Automotive	●			Turkey
[51]	TOPSIS-Grey Theory	General	●			Italy
[52]	Fuzzy System	General	●			China
[53]	AHP - MILP	General	●			China
[54]	Fuzzy-TOPSSIS	General		●		Taiwan
[52]	Fuzzy Objective Linear Programming	General	●			India

Table 1. Use of MCDM methods in supplier selection at different DM levels.

to identify the cause-and-effect relationships between different criteria in manufacturing, and so on. At the tactical level, the decisions considered are related to the production rate, demand forecast errors, utilization of manufacturing facilities and administrative constraints. MCDM methods are widely applied at the tactical level of manufacturing decision-making. At the operational level, the decisions considered are related to the rejection rate during manufacturing, cycle time and machine breakdown.

Table 2 shows the categorization of papers in terms of decision-making level, MCDM methods used, application area/sector and country in manufacturing.

3.3. Warehousing

Due to high client expectations, warehousing decisions are vital for organizations. At the strategic level, the decisions the authors and researchers in the literature considered were warehouse location selection, space utilization and urban distribution center location. Warehousing decisions have a long-term impact on the overall SC, and as a result, trade-offs must be made between conflicting alternatives. At the tactical level, the decisions considered were warehouse layout design, cost per order and response rate. Many authors applied MCDM methods for tactical warehousing decisions. At the operational level, the decisions considered were damages, reconciliation error and order fulfillment rate. Only a few applications of MCDM methods can be found in the literature on warehousing decisions at the operational level. **Table 3** shows the categorization of papers in terms of decision-making level, MCDM methods used, application area/sector and country in warehousing.

3.4. Logistics

Logistics plays an important role in overall SC performance. At the strategic level, the decisions researchers considered were logistics provider selection, service reliability and freight cost.

Papers	MCDM methods used	Sector/application area	DM level			Country
			Strategic	Tactical	Operation	
[56]	DEMATEL- ANP & Grey Relational Analysis- TOPSIS	General	●			China
[57]	SAW- WASPAS- TOPSIS	PVC windows manufacturing	●			Poland
[58]	AHP-DEMATEL	Paint shop	●			India
[59]	FAHP- PROMETHEE	Mining equipment manufacturer		●		India
[60]	AHP-TOPSIS and SWOT	Mining industry	●			Iran
[61]	AHP	Heat devices manufacturing	●			Poland
[62]	AHP-WASPAS	Laser cutting		●		Serbia
[63]	TOPSIS	Face milling			●	India
[64]	TOPSIS	Micro EDM			●	India
[65]	Fuzzy System	General	●			Denmark
[66]	Fuzzy-DEMATEL	General		●		Iran
[67]	Probabilistic Fuzzy-ANP	General	●			Philippines
[68]	Fuzzy-VIKOR	Hard disk manufacturing	●			Malaysia
[69]	Fuzzy System	General	●			UK
[70]	Fuzzy-ANP and TOPSSIS	General		●		India
[71]	DEMATEL-ANP	Rubber, tire and tube manufacturing		●		Denmark
[72]	AHP	Mining industry		●		India
[73]	Fuzzy Decision Tree	Aircraft	●			UK
[74]	Fuzzy-DEMATEL	General	●			Taiwan
[75]	Type 2 Fuzzy hybrid experts system	Steel manufacturing		●		Iran
[76]	Fuzzy Based Genetic Algorithm	General	●			Bangladesh
[77]	Fuzzy System	General		●		Finland
[78]	Fuzzy-TOPSIS	Cement manufacturing	●			India
[79]	Fuzzy DEMATEL	Automotive	●			Iran
[80]	ANP - VIKOR	Textile		●		USA
[81]	ANP-DEMATEL	Manufacturer of medical consumables		●		Taiwan
[82]	DEMATEL	General		●		Taiwan
[83]	Fuzzy - MP	General	●			Turkey
[84]	Fuzzy Sets	General		●		Spain
[85]	Fuzzy System	General		●		UK

Papers	MCDM methods used	Sector/application area	DM level			Country
			Strategic	Tactical	Operation	
[86]	Fuzzy - MP	Automotive			●	Spain
[87]	Fuzzy Linear Programming	Textile industry		●		Malaysia
[88]	Fuzzy linear regression, Fuzzy time series and Fuzzy grey GM	General		●		Turkey
[89]	Fuzzy-AHP	Electronics		●		Taiwan
[90]	Fuzzy integrated model with fuzzy objective function	Home Appliance Company		●		Azerbaijan

Table 2. Use of MCDM methods in manufacturing at different DM levels.

Papers	MCDM methods used	Sector/application area	DM level			Country
			Strategic	Tactical	Operational	
[91]	Fuzzy	Winery's warehouse	●			Argentina
[92]	AHP	Automotive	●			Others
[93]	AHP	General	●			India
[94]	FAHP and FTOPSIS	General	●			India
[95]	FAHP and FANP	General	●			Turkey
[96]	FAHP	Injection molded parts mfg.	●			Pakistan
[97]	FAHP	Retail industry	●			Serbia
[98]	Fuzzy	General	●			India
[99]	Fuzzy Multi-attribute	General	●			China
[100]	Fuzzy	General	●			Italy
[101]	Electre III	General		●		Poland
[102]	FANP	General	●			Iran
[103]	FTOPSIS - MCGP	Airline		●		Taiwan
[104]	AHP	Logistics service provider		●		Bangladesh
[105]	TOPSIS	Retailing channel	●			Taiwan
[106]	Fuzzy System	Logistics service provider		●		Taiwan
[107]	FTOPSIS	Home appliances	●			Iran
[108]	Fuzzy random multi-objective DM model	Constructions		●		China
[109]	FTOPSIS	Automotive	●			Turkey
[110]	FTOPSIS	General	●			India
[111]	Fuzzy System	Logistic company	●			Canada

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Papers	MCDM methods used	Sector/application area	DM level			Country
			Strategic	Tactical	Operational	
[112]	FTOPSIS	Logistic company	●			Canada
[113]	FTOPSIS	General	●			Turkey
[114]	Fuzzy-TOPSSIS	IC Packaging Plant	●			Taiwan
[115]	Fuzzy	General	●			Taiwan
[116]	Fuzzy System	General		●		Jordon
[117]	Fuzzy inference system	General			●	India

Table 3. Use of MCDM methods in warehousing at different DM levels.

Many authors applied MCDM methods and techniques at the strategic level of decision-making in logistics. At the tactical level, decisions considered relate to logistics network design, mode of transport and establishment of logistic centre. At the operational level, the decisions considered were damages, delayed shipment rate, cost per delivery and operational performance (wrong delivery rate, for instance). A few authors applied MCDM techniques at the operational level. **Table 4** shows the categorization of papers in terms of decision-making level, MCDM methods

Papers	MCDM methods used	Sector /application area	DM Level			Country
			Strategic	Tactical	Operational	
[118]	FAHP	Land transport provider	●			Columbia
[119]	DEA	General	●			Valencia
[120]	FAHP	General	●			Thailand
[121]	FQFD-TOPSIS	Agriculture	●			France
[122]	FAHP	General	●			France
[94]	FAHP and FTOPSIS	General	●			India
[123]	FAHP-VIKOR	Electronics industry	●			India
[124]	ANP-BSC	Logistics industry	●			Turkey
[125]	FAHP-TOPSIS	Logistic provider	●			Columbia
[126]	AHP	Logistics industry	●			Turkey
[127]	FDelphi-AHP	General	●			Brazil
[128]	FAHP	Military logistics		●		Taiwan
[129]	FAHP-SWOT	Manufacturer of composite pipes	●			USA
[130]	AHP-DEMATEL	General	●			India
[131]	DEMATEL and FANP	Telecommunication	●			Turkey
[132]	Electre III	General	●			Romania
[133]	Fuzzy			●		Taiwan

Papers	MCDM methods used	Sector /application area	DM Level			Country
			Strategic	Tactical	Operational	
		Semiconductor manufacturing				
[134]	Fuzzy-VIKOR	General	●			New Zealand
[135]	FAHP and FTOPSSIS	Tire manufacturing		●		Turkey
[136]	Fuzzy DEMATEL, Fuzzy ANP and Fuzzy VIKOR	City logistics	●			Serbia
[137]	FAHP	Logistics company	●			Thailand
[138]	FAHP and FTOPSIS	City Logistics	●			Serbia
[139]	TOPSIS-AHP	Telecommunication	●			India
[140]	AHP	Aerospace		●		USA
[141]	QFD - FAHP	Hard disk component manufacturer	●			UK
[142]	FAHP	FMCG	●			Bangladesh
[143]	FAHP	Garment material manufacturing		●		China
[144]	Fuzzy-Delphi	Logistic company	●			Turkey
[145]	FTOPSIS	Logistic company	●			Turkey
[146]	FTOPSIS	Automotive			●	India
[147]	AHP-TOPSIS	Automotive		●		Turkey
[148]	FAHP	Logistic Company			●	Turkey
[149]	FTOPSIS	Logistic Company			●	Turkey
[150]	FAHP	Logistic Company	●			Turkey
[151]	ISM-Fuzzy	Battery manufacturing company		●		Denmark
[152]	ANP	FMCG			●	India

Table 4. Use of MCDM methods in logistics at different DM levels.

used, application area/sector and country in supplier selection, manufacturing, warehousing, and logistics, respectively.

4. Quantitative result analysis

Today, competition is shifting from individual company performance to SC performance, thus making it essential for companies to measure their SC performance effectively and efficiently. To that end, they need to identify appropriate methods for evaluating the measurement of the

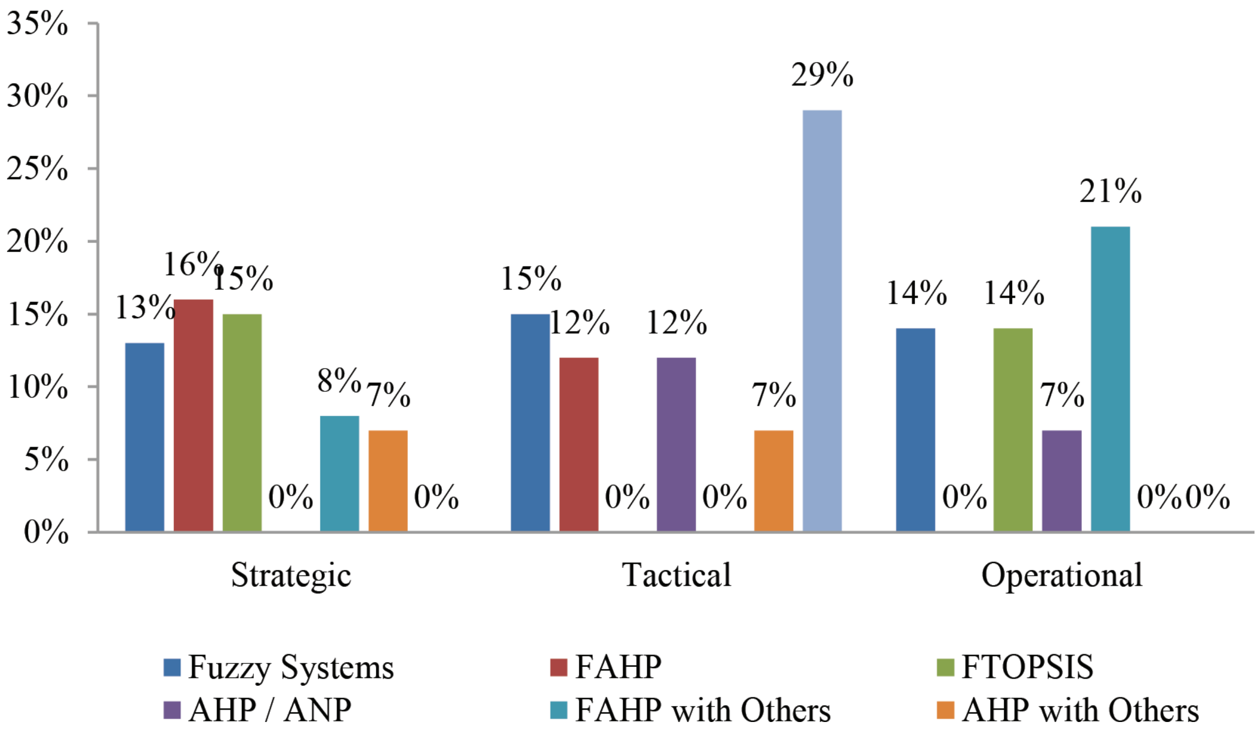

Figure 6. MCDM approach at the strategic, tactical and operational level.

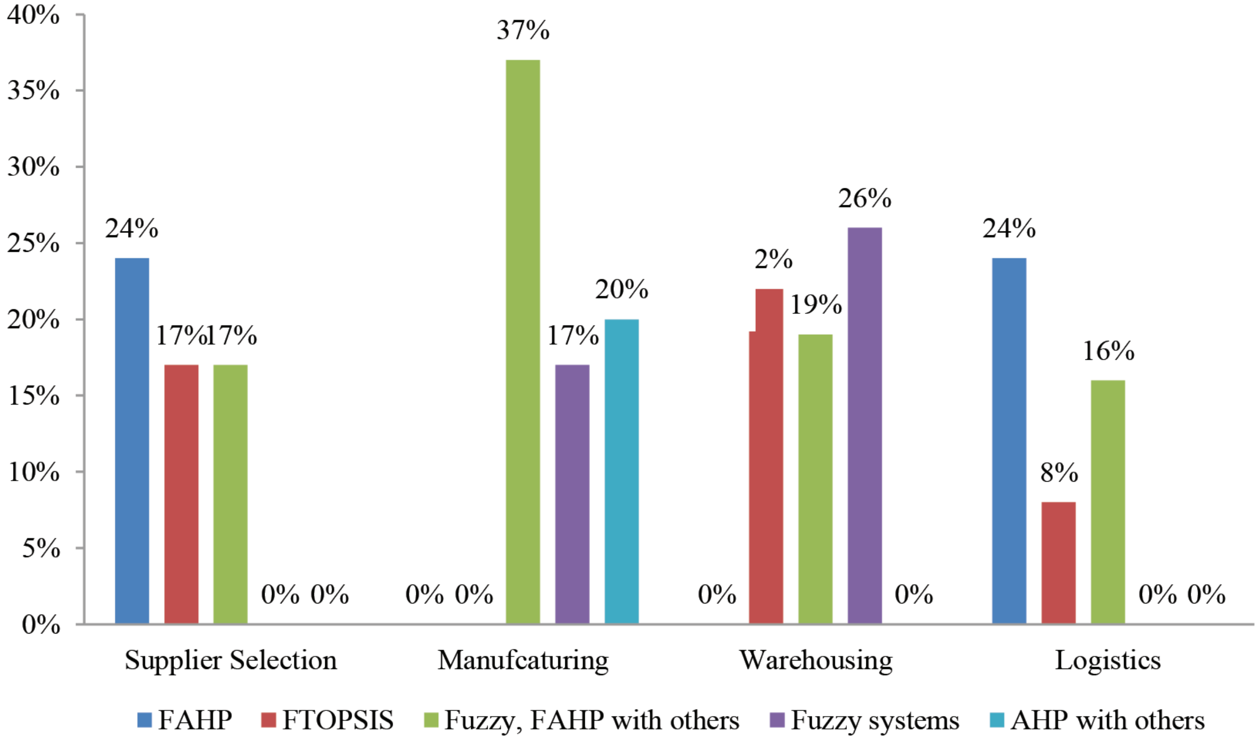

Figure 7. Top three MCDM methods of considered SC functions.

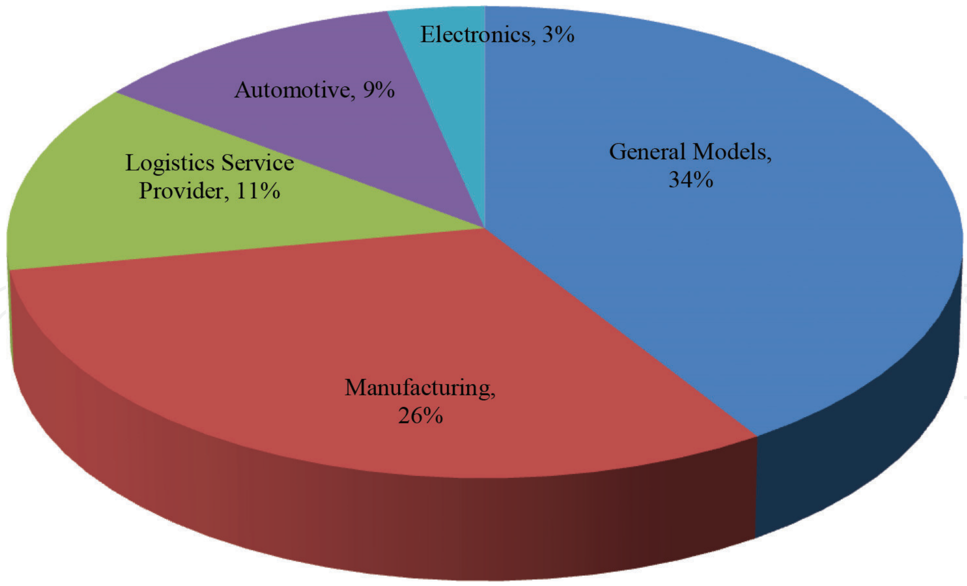

Figure 8. Paper distribution of the application areas for MCDM methods.

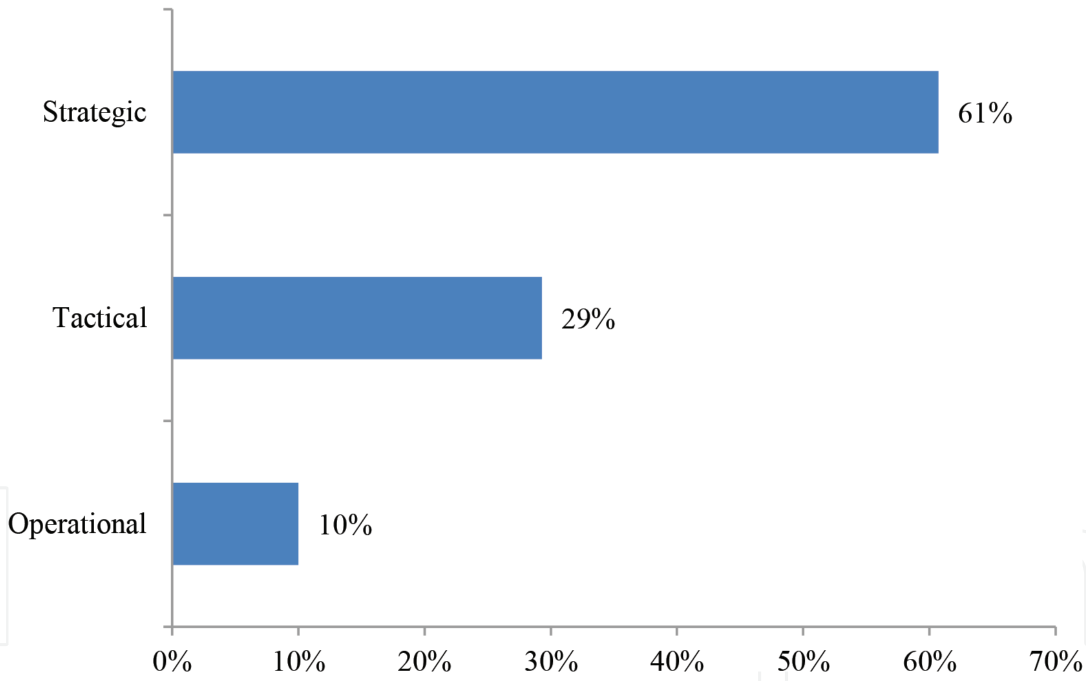

Figure 9. Paper distribution at different levels of DM.

performance of the entire SC cycle. This study will help managers, practitioners and researchers select the most appropriate MCDM method for managing their SC cycle and analyze the results quantitatively in the following aspects.

a. **Figure 6** shows the percentage of papers covering each MCDM methods at different strategic, tactical and operational levels of SC decisions.

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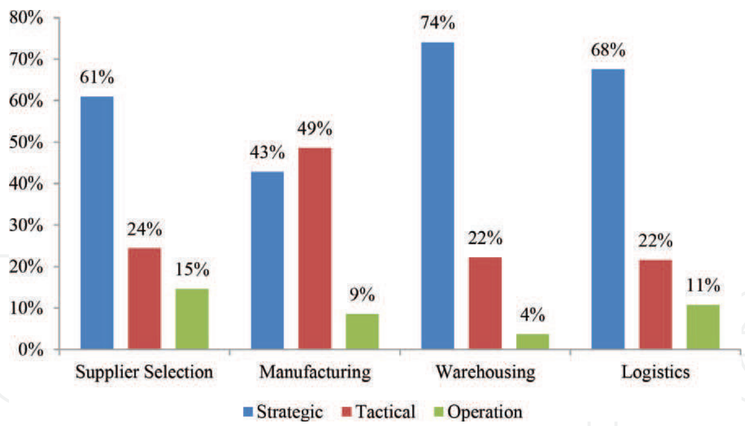

Figure 10. Paper distribution at different levels of DM of considered SC functions.

b. **Figure 7** shows the top three MCDM methods for considered SC functions which are supplier selection, manufacturing, warehousing and logistics.

c. **Figures 8** and **9** show the paper distribution of the application areas for MCDM methods and its distribution at different levels of DM.

d. **Figure 10** shows the paper distribution at different levels of DM in considered SC functions.

After summarizing the methods at the strategic, tactical and operational levels of decision-making, researchers and practitioners can now easily select most widely used MCDM methods in SC decision-making. Further, this research will help managers select a suitable technique from widely used MCDM methods for supplier selection, manufacturing, warehousing and logistics.

This study considered the application of MCDM methods in almost all sectors. After an extensive literature review, we found that many authors, managers and researchers have applied MCDM methods in many sectors and at different DM levels as mentioned in **Figures 8** and **9**, respectively.

Managers and decision makers need to select the best method at each level of decision-making in the entire SC. **Figure 10** shows the use of MCDM methods at each level of decision-making in the entire considered SC cycle. We can infer from the figure that at a strategic level, 74% of papers applied MCDM methods in warehousing decisions; at a tactical level, 49% of papers used MCDM methods in manufacturing; and at an operational level, 15% of papers used MCDM methods in supplier selection.

5. Discussion

The systematic literature review on the application of MCDM methods in supply chain management demonstrates the richness of MCDM to take different DM perspectives in the decision process. At the early stage of application, most of the methods focus on the fragmented SC structure with inefficient processes at the supply, manufacturing, warehousing and logistics levels. The subsequent integration of SC processes motivates the application of MCDM to improve the global decision process (more holistic). However, the integration comes with many challenges. First, more criteria have to be considered in the decision process. Second, the number of decision makers increases.

For long-term decisions (strategic and tactical), the decision process involves many criteria resulting from the information collected through the different SC functions. Also, most often, different decision makers (SC actors) are involved in the decision process. Thus, the use of MCDM methods is more suitable for long- and mid-term decisions (around 90%). However, the application of MCDM for short-term decisions (operational/real time) is limited to only 10%. Indeed, operational decisions are made very rapidly, and only partial information is usually available due to lack of data. Thus, the application of MCDM is not predominant and sometimes more difficult to implement.

For the supplier selection process, a detailed analysis (**Figure 10**) shows that MCDM methods are commonly used for long-term (strategic and tactical) decisions (85%). This result can be explained by the intensification of global commerce due to globalization and ever-greater competition, where supplier selection is critical. Thus, the appropriate supplier selection plays a vital role in organizational success. Conversely, the smallest number of researchers and DMs (15%) used MCDM methods at the operational level because of the fact that supplier selection and evaluation decisions have an impact on product quality, delivery, cost of material and service level. Therefore, decisions such as make-or-buy and the establishment of long-term contracts with suppliers must be aligned with the strategic goals of an organization and cannot merely be taken at the operational level.

Regarding the manufacturing process, long-term (strategic and tactical) decisions are also critical and include the development of technology selection and capacity expansion strategies to overcome shortage, minimize cost and maximize overall production efficiency. Again, the literature review analysis shows that 91% of MCDM methods are applied for long-term (strategic and tactical) decisions. For short-term manufacturing decisions, we are usually in the execution process of production, and there is less flexibility in decision-making. Thus, we notice that only 9% of the studies used MCDM methods for short-term decision-making (operational level).

Long-term warehousing decisions include the location and the design (technology choice and capacity) of the facility, which is one of the drivers of SC management. Moreover, the number of facilities (Warehouses and Distribution Centers) determines the total cost and the response time. For that reason, different criteria are used to make appropriate decisions. A significant amount of MCDM methods are applied in this context (96%). However, only 4% of papers applied MCDM methods at the operational level has been reported in our study.

For logistics activities, **Figure 10** shows that many researchers and decision makers applied MCDM methods for long-term (strategic and tactical) efforts (approximately 90%). An effective and efficient logistics system requires long-term planning by considering future expansions, mergers and globalization. Long-term decisions help organizations reduce transportation cost and increase delivery service. For short-term decisions (operational), decision makers are obliged to take rapid action because of uncertainty caused by the manufacturing or logistics service provider. Therefore, this study shows that 11% of researchers and decision makers applied MCDM methods for short-term DM (operational), which is the highest among all considered SC functions.

6. Limitations and further research directions

This chapter has a number of limitations, detailed as follows:

i. This review is limited to academic reviewed journals and conferences. Therefore, unpublished work, non-reviewed articles, working papers and practitioners' articles can be included in a future extension of this research.

ii. This review spanned 13 years (2005–2017), and we believe it is representative of the literature on the application of MCDM methods in SCM. Although this study is not exhaustive, it is however comprehensive (140 papers) enough to allow a conclusion.

iii. In the allocation of DM levels (strategic, tactical, and operational) in a particular paper, we followed the definition of DM level by David Simchi-Levi, Kaminsky, & Simchi-Levi (2008).

6.1. Future research directions

In SC, there are many criteria that have to be considered while making decisions. These criteria are often conflicting in nature, and MCDM methods and their integration with other methods are able to provide a framework for DMs in solving SCM problems and challenges. Moreover, with more globalization and digitalization, data availability is increasing, and the potential application of MCDM methods in tackling SCM problems under uncertainties becomes inevitable but needs a transformation. Based on this study, the following future research directions are proposed:

i. In future, selected papers of this study can be further analyzed to know uncertain criteria that have been used for internal and external uncertainty in considered SC functions.

ii. Analyzed papers were further examined to know the exact criteria that were considered by DM in considered SC functions.

Notwithstanding the above-mentioned limitations and future research direction, we strongly believe that this study is in a very important area, namely, applications of MCDM methods in SCM, and should fill a gap in the literature.

7. Concluding remarks

This chapter presented a systematic literature review on the application of MCDM methods in considered SC functions, namely, supplier selection, manufacturing, warehousing and logistics. A total of 140 papers covering a time span of 13 years from a well-known database were gathered, analyzed and categorized in terms of a long-term and short-term (strategic, tactical, and operational) DM perspective, MCDM method considered and application area.

This study concludes that the research and application of MCDM methods in SCM have grown significantly in recent years. This study will help managers and decision makers select appropriate MCDM methods at a specific level of DM (strategic, tactical, and operational) and provide guidelines to managers to see which application area uses which MCDM methods. It is evident from the literature that shows that fuzzy sets and its integration with other MCDM methods have effectively and efficiently been applied at every level of the SC decision-making process as well as in the considered SC functions. This is because of the fact that due to digitalization and massive data available in the organization, perspective of SC has been totally changed. Organizations and decision makers need to change their traditional thinking when it comes to how to manage SC. Moreover, due to the availability of real-time data and information, the application of MCDM for short-term decisions will add a great value to the decision process and reduce uncertainty in managing SC. On the basis of this study, we conclude that fuzzy DM is the most appropriate MCDM method to use at different levels of DM and in building general DM models. Therefore, we believe that this systematic literature review answers all research questions that were raised and achieved the main objectives of our research.

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Prioritisation of Internal and External Barriers for Supply-Chain Implementation in Manufacturing Companies: A Malaysian Perspective

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Additional information is available at the end of the chapter

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Abstract

Manufacturing companies as well as service providers often encounter barriers in successful implementation of supply-chain management (SCM) principles and practices. This research, through extensive literature review, has identified the main barriers of SCM implementation for Malaysian manufacturing companies. Having identified the list of barriers, the items in the list are prioritised by applying the analytic hierarchy process (AHP). Ten respondents who have a wide range of experiences in dealing with SCM have provided the necessary inputs in the prioritisation exercise. The individual AHP pair-wise comparison matrices are aggregated and Superdecision software has been used to compute the priorities. From the generated ranks, the most critical barriers can easily be identified. The onus on the Malaysian manufacturing companies is to take note of the present research findings and take appropriate measures so that the full benefits of SCM can be reaped. Though the findings are valid in the Malaysian context, judgements from people from other countries can be taken and a comparison of the results can be made.

Keywords: internal barriers, external barriers, supply-chain management, analytic hierarchy process, manufacturing companies

1. Introduction

Traditionally, supply-chain management (SCM) is represented by the forward flow of materials and backward flow of information [1]. Over the years, the activities of SCM have evolved from the flow of materials, information, products and funds from supplier to manufacturer to distributer to retailer and ultimately to the end users [2]. SCM has generated much interest in recent years due to its significant benefits. Among others, the benefits include reduction in inventory, improved sharing of information, increased mutual trust among supply-chain partners, reduction of product life cycle and increased customer satisfaction [3]. These benefits have provided the impetus for organisations to invest more in their supply chain (SC) [4, 5].

Even though organisations benefit from SCM implementation, it is, however, challenging and costly [1, 4, 6–8]. Organisations often encounter barriers in implementing effective SCM [7], and these barriers exist in both intra- and inter-organisations. Lack of top management support, employee empowerment and training, financial resources and information technology infrastructure are some examples of intra-organisational or internal SCM barriers. On the other hand, inter-organisational or external barriers range from resistance to share critical information, lack of collaboration with SC partners, lack of information sharing and mistrust among SC partners [9–11]. Although a large amount of the study is available on SCM barriers, yet their mere identification and explanation are considered inadequate [7]. For example, to date, no study has been conducted to rank the barriers to SCM implementation, at least in the Malaysian context. This is important as successful SCM implementation requires managers to identify and understand which barriers are deep-rooted and destructive, besides identifying the most important barriers to be urgently addressed [12].

This chapter thus aims to determine the ranking or priority list of barriers to SCM implementation by focusing on manufacturing companies in Malaysia. The ranking and priority list is obtained by applying a well-known decision-making tool, the Analytic Hierarchy Process (AHP).

2. Literature review

2.1. Supply-chain management

A supply chain (SC) involves all activities, functions and facilities that are required in transforming goods and services from the material stage to the end, customer stage [13]. Basically, the SC consists of five main stages namely (1) supplier, (2) manufacturer, (3) distributor, (4) retailer and (5) customer [14]. The interaction of these five stages is illustrated in **Figure 1**. Producing products with shorter product life cycles, tight competition among companies and an increased level of customer satisfaction in today's market have compelled organisations to upscale their SC [4].

According to Ferguson [2], supply-chain management (SCM) is a cooperative effort by members, using different approaches, in implementing, designing and managing a value-added process to fulfil customer requirements. That is, SCM is a collaboration of product, information and financial management starting from the supplier to manufacturer to distributer to retailer and to customer [2]. A continuous development in communications technology and transport, such as the Internet and overnight delivery, are some of the strong drivers for supply-chain management and development [15].

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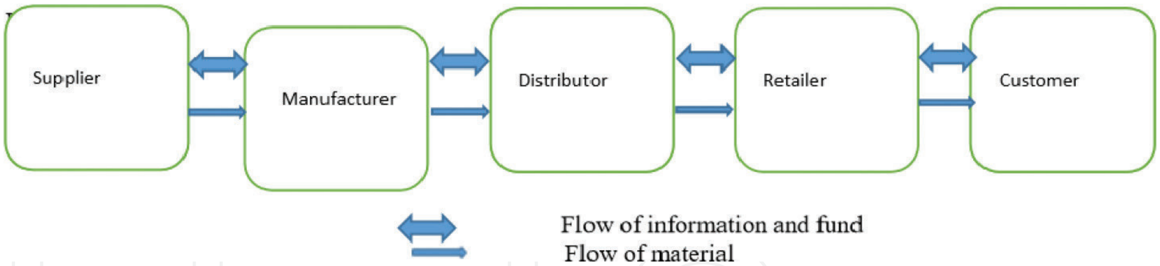

Figure 1. Five stages of supply chain [13].

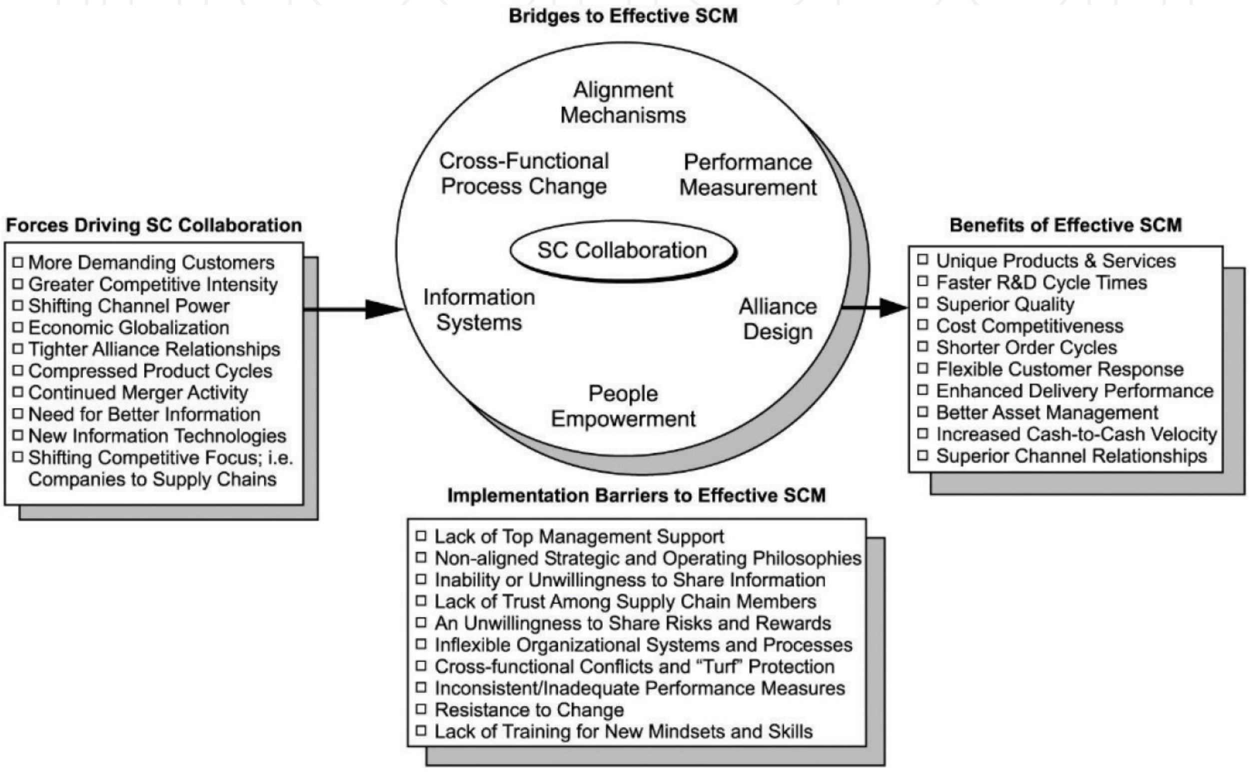

Figure 2. A framework for SCM implementation [16].

A comprehensive framework for SCM implementation developed by [16] is illustrated in **Figure 2**. The framework put SCM implementation into four stages. The first stage is the strategic management initiatives that function as the heart of SCM implementation. The second stage constitutes several factors that act as driving forces for SCM implementation such as customer demand, competition, economics and technology. The third stage is the performance outcome for SCM implementation such as faster product life cycles, higher quality and cost-effectiveness. The last stage comprises problematic factors that act as barriers disrupting the implementation of SCM namely lack of top management support, unwillingness to share information and reluctance to share risks among SC partners.

Effective implementation of SCM helps reduce inventory level, improve information sharing, fulfil customer requirements and obtain mutual trust among supply-chain partners [3]. An effective implementation of SCM has become *sine qua non* for companies in the competitive market which in turn helps them attain competitive advantage [7].

2.2. Barriers to SCM

Despite its significant benefits, the implementation of SCM is challenging, and companies continue to encounter barriers that prevent them from implementing effective SCM [8]. Ref. [7] categorised the barriers as managerial, technological, financial, organisational and collaborative, whereas [14] grouped the barriers as strategic, cultural, technological, individual and organisational [17], on the other hand, classified these barriers as structural resistors, sociological resistors, organisational routines and individual skills. These barriers exist internally as well as externally. Full benefits of SCM implementation can be achieved when companies are able to identify and overcome these barriers to stay competitive in today's changing environment [18]. These barriers are complex in nature, and thus it is crucial for managers to understand them well so that the barriers can be timely resolved [19].

Internal SCM barriers stem from limited support from management, inadequate employee empowerment and training, insufficient funds and an inferior information technology base. Additionally, the problems among organisations and partners related to their refusal to share vital information, lack of trust and non-collaboration represent the external barriers to SCM [9–11]. [7] as well as [14] analysed and listed the internal and external organisational barriers to SCM implementation obtained from prior research as exhibited in **Tables 1** and **2**, respectively.

No.	Supply-chain management barriers
1.	Lack of top management commitment and support
2.	Unclear organisational objective
3.	Resistance to change
4.	Lack of motivation and employee empowerment
5.	Poor corporate culture
6.	Mistrust among employee and SC partners
7.	Lack of education and training to employee and supplier
8.	Poor information and communication technology (ICT) infrastructure
9.	Lack of financial resources
10.	Unwillingness to implement supply-chain practices
11.	Lack of integration among SC partners
12.	Lack of collaboration among SC partners
13.	Unwillingness to share information among SC partners
14.	Lack of responsiveness
15.	Lack of customer satisfaction index

Source: [7].

Table 1. Supply-chain management barriers from previous literature.

No.	Category	Supply-chain management barriers
1.	Strategic barrier	Unclear organisation objective
		Lack of top management commitment and support
		Low customer satisfaction index
		Lack of awareness about SCM
		Short-term decision-making perspectives
		Political instability
		Lack of resource and capability
2.	Cultural barrier	Unwillingness to implement supply-chain practice
		Unwillingness to share information among supply-chain partners
		Mistrust among employees and supply-chain partners
3.	Technological barrier	Lack of information technology
		Poor ICT structure
4.	Individual barrier	Lack of education to employee and supplier employee
		Resistance to change
		Lack of motivation and employee involvement
		Unawareness among society about social practices
		Lack of awareness about environment and other sustainability issues
		Lack of necessary tools, management skills and knowledge
5.	Organisational barrier	Lack of financial gain
		Lack of framework
		Lack of measurement system
		Lack of proper organisational structure to create and share knowledge
		A lack of inter-organisational cooperation and coordination

Source: [14].

Table 2. Categorisation of barriers in manufacturing organisations.

Some researchers are also interested in investigating barriers in green supply-chain management. This is because sustainability has been reported as one of the fastest growing supply-chain management trends recently. Barriers in green supply chain can be seen from the work of several researchers such as [20–22]. Some researchers on the other hand have investigated barriers with regard to specific issues in SCM. [23], for example, constructed a model for barriers to supply-chain collaboration. Barriers to customer-responsive SCM are identified by [23], whereas barriers to logistics performance in textile supply chain are explored by [24].

Barriers to SCM implementation are also studied in various contexts including manufacturing companies as found in the work of [1, 4]. This is due to the fact that barriers that have been posited to SCM implementation mostly emerged from SCM discipline and nature [25]. Monzouri et al. [1] recorded several problematic factors that occur in manufacturing companies (refer to **Table 3**) that need to be appropriately addressed if competitive advantage is to be gained through successful SCM implementation.

Barriers/problematic factors	Description of variables
Lack of information	This factor includes information quality (accuracy, adequacy, conciseness, credibility and time line) and information sharing (trust, deep and intensity)
Lack of new equipment	New equipment or new infrastructure for applying SCM such as IT infrastructure, production systems, inventory adjustment systems, distribution systems and all other activity requirements.
Lack of expert employees	Employees should have accurate, specialist knowledge about SCM (strategy, planning, implementing, obstacles, problems, advantages, etc.) to implement SCM.
Increased product stock time	The new method of inventory adjustment (arrangement methods, bar coding systems, etc.) might take time to be established rather than old techniques.
Increased production time	Production strategy and planning might be changed during SCM application and takes time to set up.
Increased designing time	SCM implementation requires changes in the structure of product design and it takes time to be established.
Increased distribution time	Old methods of transportation such as scheduling and transportation systems should be changed according to new techniques and rules of transportation and distribution.
Increased tooling time	Many current systems of maintenance and tool making should be improved during SCM application.
Lack of time	SCM implementation demands changes to be made, and as current projects take time to be completed, there is insufficient time for SCM implementation.
High costs	SCM implementation needs expert employees, new equipment, IT infrastructure and many other requirements, thus incurring extra funds.

Source: [1].

Table 3. Barriers/problematic factors among manufacturing companies.

2.3. Analytic hierarchy process

The AHP model was developed by Thomas L. Saaty in the 1970s while working on studies for the Department of Defence and the National Science Foundation in the United States. The AHP is a model that can help decision-makers in simplifying complex problems.

Saaty [26–28] defined the AHP as a method of breaking down a complex, unstructured situation into its component parts and arranging these parts of judgements according to the relative importance of each variable. These judgements are subsequently synthesised to determine the variable that has the highest priority and that should be acted upon to influence the outcome of the situation. In a simpler way, the AHP is described as a viable technique to help decision-makers face multi-criteria decisions by decomposing the complex decision operations into a multi-level hierarchical structure. The AHP serves to quantify relative priorities of factors and alternatives within specific scales based on human judgements or evaluations. Its pair-wise comparison methodology evaluates several alternatives under particular criteria with respect to the goal [29, 30].

The noticeable merits possessed by the AHP have led researchers to emphasise the AHP as a tool that has the capacity to incorporate elements of subjectivity and intuition [30–33]. It is recommended as a technique that is able to transform subjective judgements into objective measures [31] by organising individual feelings, intuition and logic into a structured manner [34]. Last but not least, it represents a measurement theory competent for both the qualitative and quantitative criteria [35, 36], since the qualitative aspect is required to define the problem and its hierarchy while the quantitative criterion is needed to concisely express judgements and preferences besides executing the consistency test [27].

Its applicability in both individual and group decision-making has resulted in recognition and acceptance in the decision-making process [28, 37, 38]. As group-based decision-making is often achieved by considering the geometric mean of comparison values, the AHP is valued as it can measure the consistency of pair-wise decision judgements, which in turn reduces biasness in the process [28, 39].

2.3.1. Overview on the applications of analytic hierarchy process

The acceptance of the AHP as a credible managerial decision tool is proven in its applications in three main industrial sectors. For instance, in the primary sector, the AHP was successfully utilised in agricultural [40], fishing [41] and mining [42] sectors. For the secondary sector, the use of the AHP was reported in manufacturing [43, 44], the automobile industry [45] as well as in energy gas or electricity supplies [46]. Additionally, the AHP has been applied in the service industry including information and technology, software development, telecommunications, health care, banking [47] and higher education [48, 49].

The successful application of the AHP in a variety of areas has also been documented in accounting research [50], medical and health care [51, 52], operations management [53] and higher education [54]. A thorough review of the applications of the integrated AHP rather than stand-alone AHP can also be found in the works of [39]. Furthermore, a more comprehensive observation of the AHP related to its application, region, industry and integrated tools has been documented by [31, 36, 55].

AHP applications can also be seen in SCM. It is reported that the AHP was first utilised in SCM in 1993, and its application increased dramatically after 2003 onwards [56]. The use of AHP in several SCM areas can be categorised into five main clusters as suggested by [56]. The first SCM cluster area that highly utilises AHP is supplier or vendor selection. Masella and Rangone [57] claimed to be the pioneers for this cluster. Some recent works that applied AHP in supplier selection include [58, 59]. In fact, [60] produced a review of AHP applications in vendor and supplier selection. In most cases, researchers combined the AHP with another tool such as goal programming [61] and fuzzy logic [62] rather than stand-alone AHP, thus helping to increase credibility of the findings.

Second, green supply chain is another SCM cluster that applied AHP, with [63] identified as its pioneer. Govindan et al. and Wang et al. [64, 65] are some researchers that utilised AHP for green supply-chain management. Ref. [56] found [66] as the pioneer for the third cluster where AHP is applied, that is, in supply-chain development, performance measurement, value chain and supplier collaboration. The fourth cluster had [66] as the pioneers, with several topics identified such as supply chain and distribution network, warehouse location and customer service. Lastly, [56] identified and categorised supplier distribution centre network, supply-chain integration and collaborative planning, forecasting as well as replenishment as the topics that applied AHP in the fifth cluster.

The wide range of AHP applications in various SCM areas emphasises the significant use of the AHP in facilitating decision-making. The above actual applications embraced and validated the AHP as a methodology that can produce insightful results for real-world decision-making problems particularly in the SCM area. The visible merits and a wide range of applications have provided the impetus for using the AHP as a decision-making tool in this study.

3. Research methodology

Quantitative approach has been used in this study. To begin with, the internal and external barriers were firstly identified on the basis of a literature review. These barriers were then brought to and validated by academics that are experts in the area of SCM and relevant practitioners in manufacturing companies who are involved in supply-chain activities.

Subsequently, these identified internal and external barriers were used to design the AHP survey questionnaire. The AHP data were obtained via structured interviews with five academics that are experts in the area of SCM and five practitioners heavily involved in supply-chain activities in manufacturing companies. These academics and practitioners were selected by utilising a purposive sampling technique. The use of a purposive sampling technique is appropriate since the AHP requires opinions from experts possessing the necessary information [67]. Furthermore, acquiring responses from various groups of academics and practitioners is considered common and acceptable in AHP as it enables the exploration and identification of multiple perspectives on the internal and external barriers to SCM implementation in manufacturing companies [39].

Descriptive analysis such as frequency and percentage will be used to explain respondents' demographic information. AHP data, on the other hand, were analysed by utilising the four AHP stages as recommended by [28] in prioritising the internal and external barriers to SCM implementation.

The four stages of analysing the AHP data are as follows:

a. Define the problem and determine the kind of knowledge sought.

b. Structure the decision hierarchy. The hierarchy is a tree-like structure that comprises several levels. The first level represents the goal of the decision or in other words the purpose of applying the AHP in a particular project, followed by the criteria, sub-criteria and then the alternatives that are located at the lowest level of the hierarchy. The AHP hierarchy model is illustrated in **Figure 3**.

c. Construct pair-wise comparison matrices (PCMs). Each element at an upper level is used to compare the elements in the level immediately below it. A pair-wise comparison matrix

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($n \times n$) is constructed for the lower levels with respect to one in the level immediately above. The pair-wise comparison matrix A in which element a_{ij} of the matrix was the relative importance of the ith factor with respect to the jth could be calculated as

$$A = (a_{ij}) = \begin{bmatrix} a_{11} & a_{12} & \cdot & \cdot & a_{1n} \\ a_{21} & a_{22} & \cdot & \cdot & a_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ a_{n1} & a_{n2} & \cdot & \cdot & a_{nn} \end{bmatrix} (i, j = 1, 2, \ldots, n) \quad (1)$$

The pair-wise comparisons generate a matrix of relative priorities for each level of the hierarchy. The number of matrices depends on the number of elements at each level. The order of the matrix at each level depends on the number of elements at the lower level that it links to. In terms of judgement, there are $C(n, 2)$ or $n(n-1)/2$ judgements that need to be made in a set of matrix size $n \times n$.

d. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then, for each element in the level below, add its weighed value and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the lowest level are obtained.

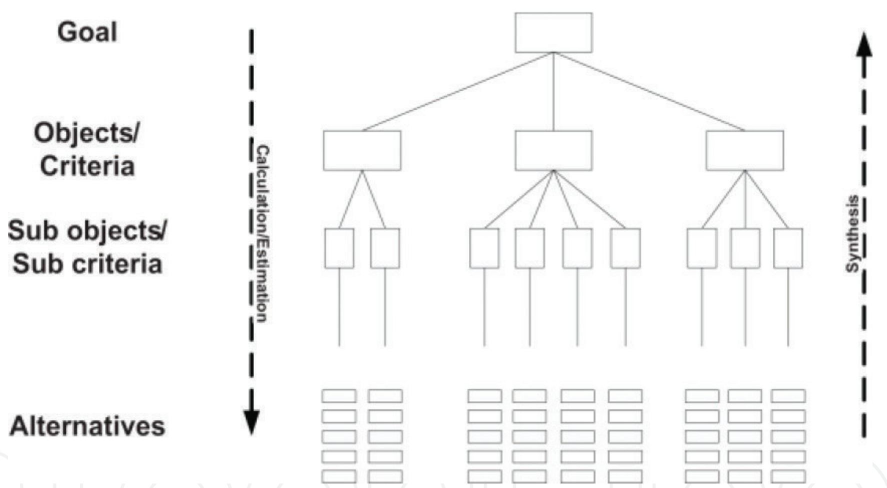

Figure 3. Hierarchy of AHP. Source: [32].

3.1. Group judgements

The AHP also allows a group of individuals to participate in a decision-making process [27]. In this case, each member is required to complete his or her own judgements in their individual comparison matrix. The individual pair-wise comparison matrices were then compiled to perform a group of pair-wise comparison matrix for each level of hierarchy. Next, each entry in the individual pair-wise comparison matrix was aggregated by using the geometric mean. This is conducted to determine the respective entries in the group pair-wise comparison matrices for all the identified criteria and sub-criteria [28, 37, 38].

4. Results and discussion

As mentioned above, the internal and external barriers of SCM implementation at Malaysian manufacturing companies were identified through literature review and subsequently got validated by academics and practitioners. The barriers are shown in **Figure 4** inside the screenshot of Superdecision software.

In order to rank the internal and external barriers of SCM for a Malaysian manufacturing industry, 10 respondents were contacted whose demographic information is provided in **Table 4**. As we see that the majority of the respondents are either Master's degree or PhD degree holders (9 out of 10). **Table 4** also shows that the respondents comprised one supply-chain manager, one senior estate manager, two business consultant and trainers, one environment and safety consultant and the rest five professors/associate professors in universities. All the academicians involved in the survey teach operations management and by virtue of their profession, they have practical experiences in dealing with supply-chain activities in Malaysian manufacturing industries. We also observe that all the respondents have working experiences 10 years or more. So, overall, it can be concluded that all the respondents participated in the present survey have sufficient expertise in organisation's supply-chain management.

When there are multiple respondents in an AHP survey, all the pair-wise comparison matrices need to be aggregated by using geometric means of the individual pair-wise comparisons [28, 37, 38]. **Tables 5–7** provide the aggregate pair-wise comparison matrices (PCMs) for all the 10 respondents. All the aggregated judgements were entered into Superdecision software version 2.8. The screenshots for the comparison between internal and external barriers, and comparisons among internal as well as external barriers are provided in **Figures 5–7**. The figures also show the priorities of the factors compared. For clarity purpose, the internal and external barriers and their corresponding priorities and ranks are shown in **Table 8**.

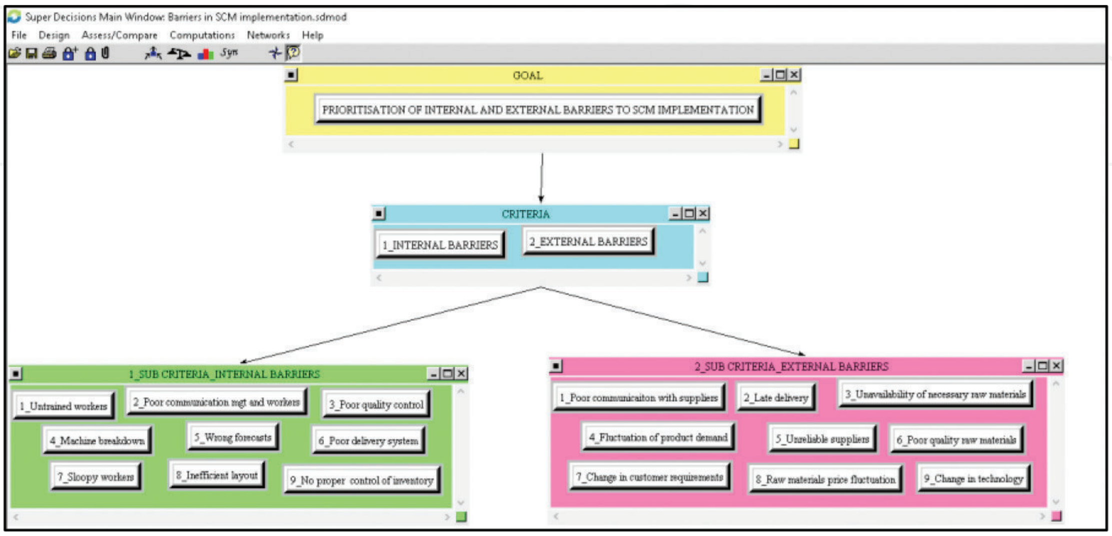

Figure 4. Internal and external barriers in SCM implementation.

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Demographic profile	Frequency	Percentage
Gender		
• Male	9	90.00
• Female	1	10.00
Race		
• Malay	4	40.00
• Chinese	—	—
• Indian	4	40.00
• Others	2	20.00
Age group		
• 21–30 years	—	—
• 31–40 years	—	—
• 41–50 years	3	30.00
• 51 years and above	7	70.00
Educational level		
• Certificate/diploma	1	10.00
• Bachelors	—	—
• Master's	5	50.00
• PhD	4	40.00
Type of employment		
• Public sector	4	40.00
• Private sector	5	50.00
• Others	1	10.00
Working experience		
• 1–5 years	—	—
• 6–10 years	—	—
• 10–15 years	5	50.00
• 15 years and above	5	50.00
Designation		
• Supply-chain manager	1	10.00
• Senior estate manager	1	10.00
• Business consultant and trainers	2	20.00
• Environment and safety consultant	1	10.00
• University professor/associate professor	5	50.00

Table 4. Demographic information of the respondents.

	C1	*C2*
C1	1	0.9603
C2		1

Table 5. PCM for two categories (internal and external).

	C11	*C12*	*C13*	*C14*	*C15*	*C16*	*C17*	*C18*	*C19*
C11	1	1.6487	0.4507	2.1885	0.7469	0.9815	2.589	2.1779	0.8152
C12		1	0.6297	0.9437	0.9568	1.8882	1.5368	0.9895	0.8572
C13			1	1.3681	1.1962	1.2993	1.1671	0.7575	1.1837
C14				1	0.4122	0.6332	0.2969	0.4695	0.533
C15					1	0.896	0.7435	0.9158	1.096
C16						1	1.1746	1.6531	0.8319
C17							1	3.2664	1.8131
C18								1	0.6297
C19									1

Table 6. Aggregate PCM for internal barriers.

	C21	*C22*	*C23*	*C24*	*C25*	*C26*	*C27*	*C28*	*C29*
C21	1	1.0704	0.7653	1.1279	0.8902	0.3006	0.9099	0.7177	0.7972
C22		1	0.7542	1.3865	1.4538	0.5207	1.8829	1.2267	0.8809
C23			1	1.2569	0.6165	0.3129	0.786	1.5651	1.9775
C24				1	0.6893	0.2577	0.4102	0.5769	1.1487
C25					1	0.4251	0.6534	0.9903	0.8992
C26						1	1.6219	1.6166	1.3266
C27							1	1.1567	1.0831
C28								1	0.6302
C29									1

Table 7. Aggregate PCM for external barriers.

From the global priorities of the internal barriers, it is observed that the five most critical barriers are (arranged in a descending order of criticality) the following:

1. Untrained workers
2. Poor-quality control
3. Inefficient layout of the factory
4. Lack of collaboration in the supply chain
5. Wrong forecasts

On the other hand, the five most critical external barriers are the following (arranged in a descending order of criticality):

1. Poor-quality raw materials
2. Change in customer requirements
3. Late delivery
4. Unavailability of necessary raw materials
5. Change in technology

Next, we have arranged all the internal and external barriers according to their corresponding global priorities. **Table 9** provides the ranking of all the barriers. From **Table 9**, it is clear that the most serious barrier is 'Poor quality raw materials'. This observation is also supported by [1]. It is also found that the least critical barrier is 'Machine breakdown'. This does not mean that 'Machine breakdown' is not serious; it merely shows that the other barriers considered (internal and external) are more serious compared to it. Once again, considering all the internal and external barriers together, we provide the following 10 most critical barriers:

1. Poor-quality raw materials
2. Untrained workers
3. Poor-quality control
4. Sloppy workers
5. Change in customer requirements
6. Late delivery
7. Unavailability of necessary raw materials
8. No proper control of inventory
9. Wrong forecasts
10. Change of technology

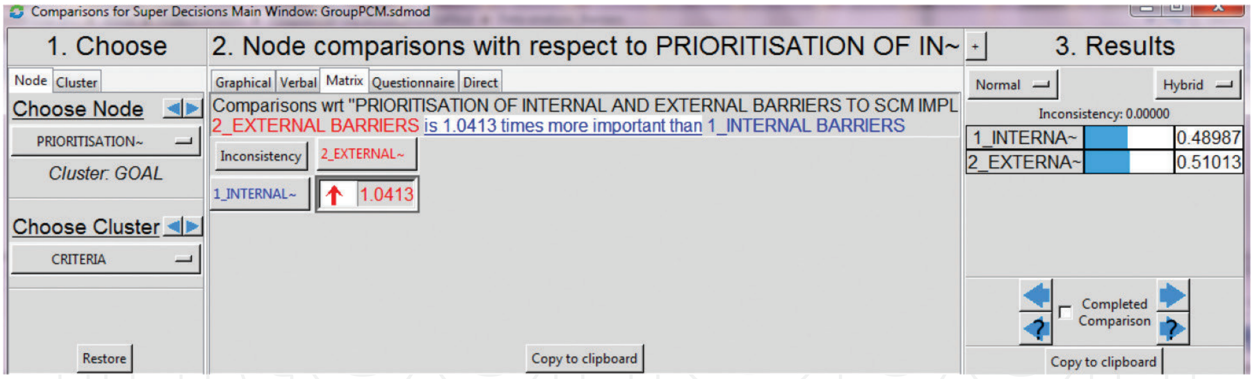

Figure 5. Superdecision screenshot for the comparison of internal and external barrier categories.

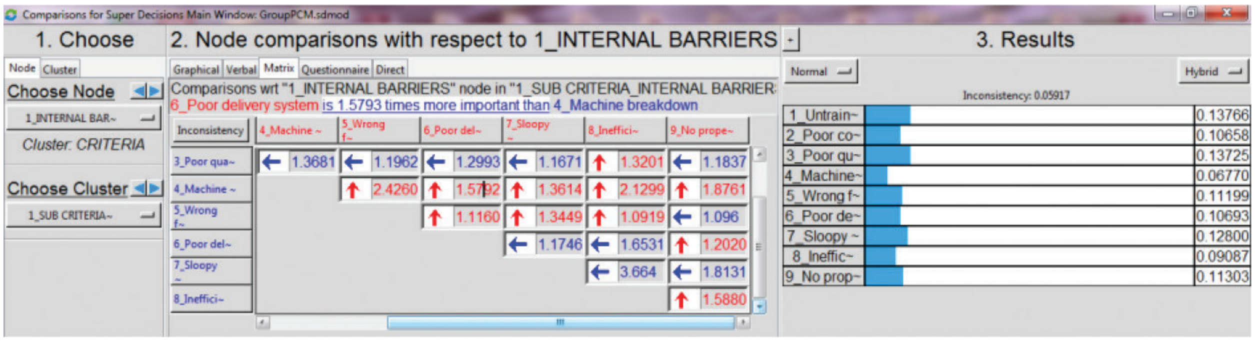

Figure 6. Superdecision screenshot for the comparison of internal barriers.

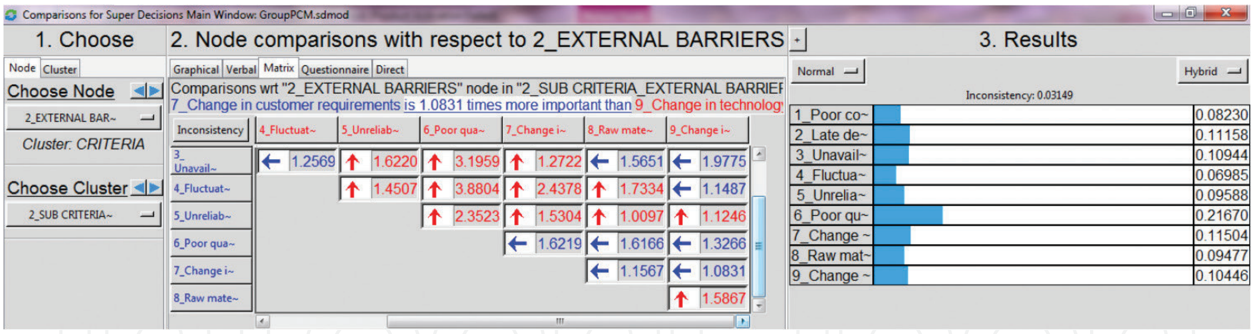

Figure 7. Superdecision screenshot for the comparison of external barriers.

Barrier	Local priority	Global priority	Rank
INTERNAL	**0.4899**	—	
• Untrained workers	0.1377	0.0674	1
• Poor communication between management and workers	0.1066	0.0522	7
• Poor quality control	0.1372	0.0672	2
• Machine breakdown	0.0677	0.0332	9

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Barrier	Local priority	Global priority	Rank
• Wrong forecasts	0.1120	0.0548	5
• Poor delivery system	0.1069	0.0524	6
• Sloppy workers	0.1280	0.0627	3
• Inefficient layout of the factory	0.0909	0.0445	8
• No proper control of inventory	0.1130	0.0554	4
EXTERNAL	0.5101	—	
• Poor communication with suppliers	0.0823	0.0420	8
• Late delivery	0.1116	0.0569	3
• Unavailability of necessary raw materials	0.1094	0.0558	4
• Fluctuation of product demand	0.0698	0.0356	9
• Unreliable suppliers	0.0959	0.0489	6
• Poor-quality raw materials	0.2167	0.1106	1
• Change in customer requirements	0.1150	0.0587	2
• Raw material price fluctuation	0.0948	0.0484	7
• Change of technology	0.1045	0.0533	5

Table 8. Local and global priorities of the internal and external barriers.

No.	Barrier	Category	Global priority	Rank
1	Poor-quality raw materials	External	0.1106	1
2	Untrained workers	Internal	0.0674	2
3	Poor-quality control	Internal	0.0672	3
4	Sloppy workers	Internal	0.0627	4
5	Change in customer requirements	External	0.0587	5
6	Late delivery	External	0.0569	6
7	Unavailability of necessary raw materials	External	0.0558	7
8	No proper control of inventory	Internal	0.0554	8
9	Wrong forecasts	Internal	0.0548	9
10	Change of technology	External	0.0533	10
11	Poor delivery system	Internal	0.0524	11
12	Poor communication between management and workers	Internal	0.0522	12
13	Unreliable suppliers	External	0.0489	13
14	Raw material price fluctuation	External	0.0484	14
15	Inefficient layout of the factory	Internal	0.0445	15

No.	Barrier	Category	Global priority	Rank
16	Poor communication with suppliers	External	0.0420	16
17	Fluctuation of product demand	External	0.0356	17
18	Machine breakdown	Internal	0.0332	18

Table 9. Ranking of all the 18 barriers.

Note that the distribution of these 10 barriers has been evenly distributed between internal and external categories.

5. Conclusions

Business environment in the twenty-first century is competitive which has further been compounded by the impetus of the fourth Industrial Revolution or IR 4.0. The situation is not an exception for the Malaysian manufacturing companies. The reason for considering manufacturing companies in Malaysia is that the lion's share of Malaysia's GDP comes from its manufacturing sector. Therefore, for sustainable performance of these companies, they need to apply best management practices relentlessly. Otherwise, at the passage of time, especially when Malaysia has opened up its manufacturing sector to foreign companies, the indigenous manufacturing companies will lose their competitive edge.

Many empirical research works have shown the substantial benefits that effective SCM practices can bring to an organisation. However, to achieve the optimum outputs in terms of supplier management, handling of inventory and customer satisfaction, the organisations must be aware about the barriers in successful implementation of SCM practices. The findings of this research provide some useful information to Malaysian manufacturing companies in chalking out their action plans in order to overcome those barriers. Once the barriers are overcome, the companies can maintain their competitiveness and continue in contributing to the country's GDP substantially.

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Analysis of Transportation Modes by Evaluating SWOT Factors and Pairwise Comparisons: A Case Study

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Danielle Morris

Additional information is available at the end of the chapter

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Abstract

Cape Breton Island is one of the most beautiful islands in the World. The island itself has a unique geography and is located in Nova Scotia, Canada. This chapter introduces and summarizes the current transportation modes in Cape Breton Island. The transportation modes discussed include air, rail, water, truck, and intermodal modes. A SWOT matrix is applied to identify the strengths, weaknesses, opportunities, and threats related to the different transportation modes in Cape Breton Island. Then, the factors are evaluated and ranked based on pairwise comparisons in analytic hierarchy process (AHP) method, and the best strategies are defined. This research provides a unique and multidisciplinary overview of transportation modes in the region that is necessary for future quantitative investigations. Furthermore, it introduces the steps to analyze transportation modes of other areas and regions.

Keywords: transportation modes, strengths, weaknesses, opportunities, threats (SWOT), Cape Breton Island, transportation strategies, ranking, evaluation, analytic hierarchy process (AHP)

1. Introduction

The costs of transportation are considerable in supply chain management. There are several transportation modes such as air, rail, truck, water, and intermodal modes. An intermodal transportation mode consists of multiple modes of transportation (e.g., water and truck) being used. Analyzing and selecting the right transportation mode is a challenging task because there are several options to choose from [1].

Nova Scotia is a Canadian province located in the east of the country. Halifax is the capital of Nova Scotia and Cape Breton Island is a beautiful island at the eastern tip of Nova Scotia. The population of the region was 101,619 in 2011. **Figure 1** shows the map of Cape Breton Island and the surrounding areas. Cape Breton Island has a unique geography with accessibility to deep water (North Atlantic Ocean) through multiple ports, such as the port of Sydney. Sydney is a community in Cape Breton Island which is located on the east bank of the Sydney River.

1.1. Transportation modes in the region

Department of Transportation, New Brunswick [2], published a report about Atlantic Canada Transportation Strategy 2008–2018. Atlantic Canada includes Newfoundland and Labrador, Nova Scotia, Prince Edward Island, and New Brunswick. Strategic highways, railways, airports, marine ports, and ferry services have been identified in said report. Cape Breton Partnership [3] summarized the supply chain and business opportunities in the Strait Area/Mulgrave region of Nova Scotia. The area is connected to Cape Breton Island through the Canso Causeway. Logistics opportunities and recommended priority opportunities have been identified in the report.

There are some existing investigations into the transportation modes in Cape Breton Island. A majority of them have focused on one mode of transportation (e.g., rail) in the area without providing an overview of multiple modes simultaneously. The port of Sydney master plan has been defined in the Sydney Harbor, Nova Scotia report [4]. Interested readers are encouraged to refer to the executive summary of the report. In Governance Structure Port of Sydney report [5], new governance structure has been discussed. Besides, some recommendations related to the vision, mandate, financial sustainability, and transition plan have been provided. An overview of rail studies in Sydney subdivision has been provided in the Summary report [6]. The authors concluded that the loss of rail services is a serious concern for businesses in the area. Besides, the

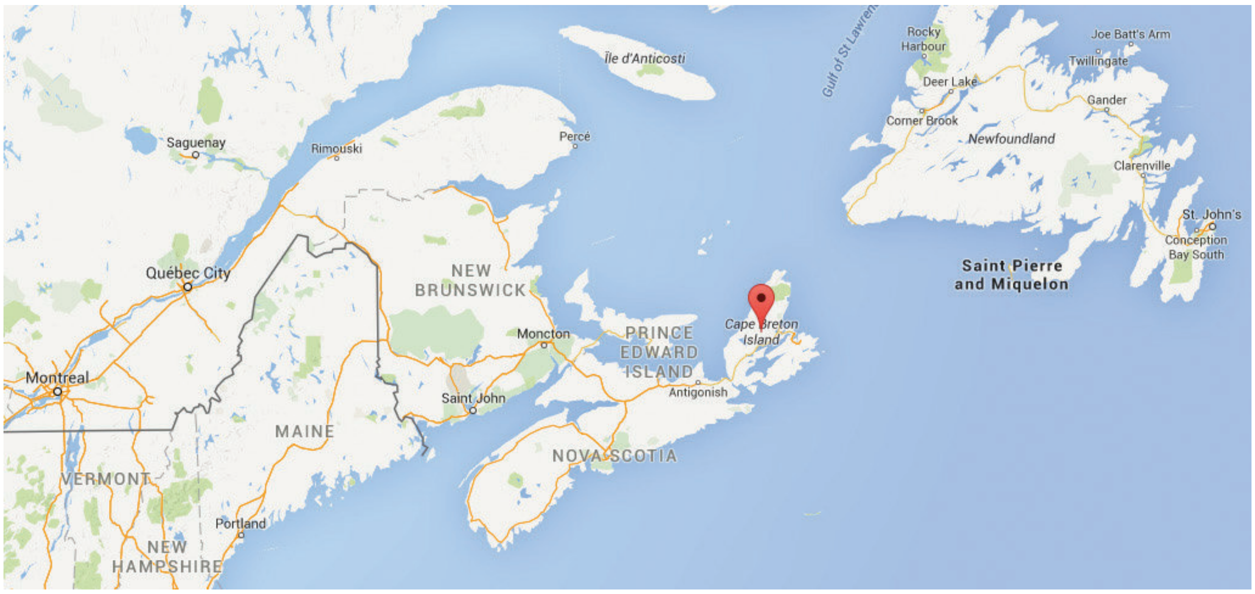

Figure 1. Cape Breton Island (source: Google Maps).

proposed container terminal can result in significant rail traffic and can lead to the reactivation of the railway. MariNova Consulting Ltd. [7] published a report about rail/truck shipping between Cape Breton Island and Mainland Nova Scotia. Rail and trucking rates, transit times (truck versus rail), as well as impacts of transloading and shipping by truck are all important parts of the report.

1.2. SWOT matrix

SWOT (strengths, weaknesses, opportunities, threats) matrix is a well-known technique for conducting a strategic study. It includes determining the objective of the company or project and identifying the internal and external factors for achieving that objective. SWOT is helpful when used to convert weaknesses into strengths, as well as threats into opportunities. SWOT matrix has several applications including strategic decision-making applications [8, 9]. SWOT analysis originated from the work of business policy academics at Harvard Business School and other American business schools in the 1960s [10]. It involves systematic thinking and comprehensive analysis of factors related to both internal and external aspects for any organization, project, or individual [11, 12]. In recent years, SWOT matrix has been utilized in different fields and has provided a good basis for strategy formulation when used properly [13]. However, inadequate development when using SWOT analysis leads to ending-up with long lists of general, even meaningless and over described factors [14]. In addition, the results of SWOT analysis would be strongly dependent on the knowledge and capabilities of the experts involved because it is a subjective approach [14, 15].

Some papers which used SWOT analysis have been classified in **Table 1**. Dadvar et al. [16] evaluated dry ports by SWOT matrix. A dry port is an inland intermodal terminal directly connected by road or rail to a seaport and operating as a center for the transshipment of sea cargo to inland destinations. Gao and Peng [11] developed a model for analyzing and ranking SWOT factors with nonhomogeneous uncertain preference information. They showed the application of the model by a numerical example. Bas [17] applied SWOT-fuzzy based method for the electricity supply chain in Turkey. Diakaki et al. [18] analyzed Vehicle Automation and Communication Systems by SWOT technique. They analyzed the problem from the motorway traffic management viewpoint. Rauch et al. [14] developed strategies for forest fuel supply chains in South East Europe by SWOT matrix. They provided both country and regional level SWOTs.

1.3. Research contributions

To our knowledge, there is no comprehensive report or publication in the literature about transportation modes in Cape Breton Island using SWOT analysis. In this chapter, we provide a unique overview of transportation modes including air, rail, truck, water, and intermodal modes in Cape Breton Island. Then, we find and rank the SWOT factors by two methods. Finally, appropriate strategies are found. This research is the first investigation that applies SWOT to analyze transportation modes in this area. The results of this research will provide bases for future quantitative investigations in the region. In addition, this chapter introduces the steps for analyzing transportation modes of other areas and regions using pairwise comparisons in AHP method.

Authors	Application	# S	# W	# O	# T	Total	Ranking the factors	Finding the strategies
Amin et al. [8]	Supplier selection	3	1	3		7	✓	
Arslan and Er [19]	Liquid chemicals	6	7	7	9	29	✓	✓
Bas [17]	Electricity supply chain	2	6	4	3	15	✓	✓
Dadvar et al. [16]	Dry ports	14	8	14	10	46		
Diakaki et al. [18]	Vehicle Automation Systems	16	10	14	12	52		
Gao and Peng [11]	Numerical example	5	4	3	5	17	✓	
Kurttila et al. [15]	Forest case	4	3	3	3	13	✓	✓
Rauch et al. [14]	Forest supply chain	13	14	10	9	46	✓	✓
Sevkli et al. [20]	Airline industry	10	10	5	5	30	✓	✓
Shahabi et al. [21]	Steel industry	3	5	3	3	14	✓	✓
Shang and Pheng [22]	Construction industry	2	4	4	2	12		
Our research	Transportation modes	14	14	14	13	55	✓	✓

S, strengths; W, weaknesses; O, opportunities; T, threats.

Table 1. Classification of some papers.

The structure of the paper is as follows: Section 2 provides summary of transportation modes in Cape Breton Island. In Section 3, SWOT matrix is introduced. In addition, the factors of the matrix are identified and ranked. Section 4 discusses the transportation strategies obtained from the SWOT matrix. Finally, Section 5 provides the conclusions and future research.

2. Transportation modes

Transportation is defined as the movement of products from one location to another location. It also refers to shipping the products from the beginning of a supply chain to the end customers and or consumers. Since few products are produced and consumed in the same location, transportation proves to play an important role in the supply chain. Moreover, transportation costs are regarded as an important part of the total supply chain cost [1]. The following sections include the summaries of the information we have collected about different modes of transportation in Cape Breton Island.

2.1. Air

There are three commercial airports in Cape Breton Island. They have been illustrated in **Figure 2**. The main airport is JA Douglas McCurdy Airport that lies just 20 min from the Sydney downtown business district. It is also located within easy driving distance to other key areas of Cape Breton Island. This airport provides flight services, which are operated by four airline companies. Air

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Canada operates five flights daily to Halifax and a year round daily flight between Sydney and Toronto, with worldwide connectivity. WestJet also provides a daily flight between Sydney and Halifax year round and another daily flight between Sydney and Toronto from May to October. Air St. Pierre currently offers two flights per week to St. Pierre from July to September and one flight per week during the rest of the year. Unlike other airline companies which just provide passenger services, Air St. Pierre also provides weekly cargo service to St. Pierre and Miquelon. In the past, Provincial Airlines executive air charter service, which travels throughout Atlantic Canada, Ontario, the eastern U.S. and Greenland [23].

The second airport is Margaree Airport, which is owned by the Inverness Municipality. The Inverness County has decided to upgrade this airport as a part of efforts to grow a tourism-based economy [24]. The third airport is Port Hawkesbury Airport that is located in the north of the town of Port Hawkesbury and a few minutes drive from the gateway of Cape Breton Island (Canso Causeway). It has the geographical advantage of being near the famous golf course (Cabot Link), fishing (Margaree River), as well as other interests on Cape Breton Island and the eastern mainland of Nova Scotia. This airport offers a large number of Biz-Jets, recreational flyers, medical and government flights during the year, as well as charter services which operate from Halifax or any other airport on the Atlantic Seaboard [25].

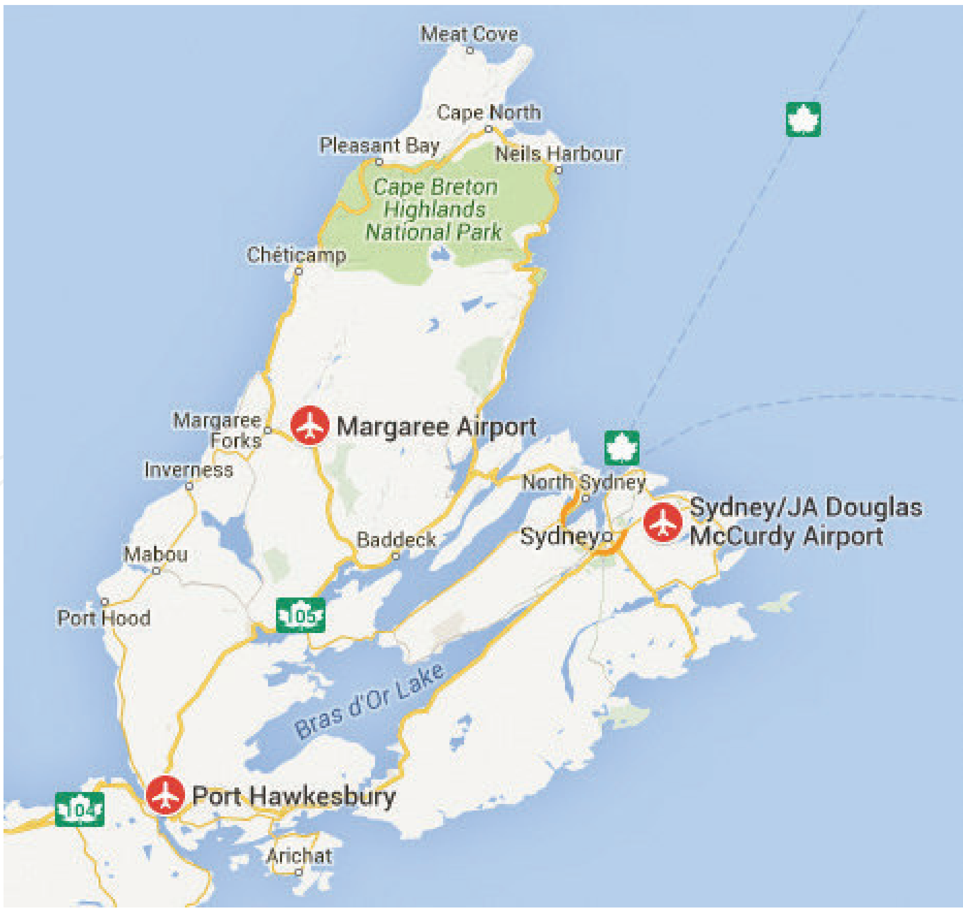

Figure 2. Airports of Cape Breton Island (source: Google Maps).

2.2. Truck

There are three controlled-access 100-series highways converging in the Sydney area, which are Highway 104, Highway 105 (Trans-Canada Highway), and Highway 125. These highways are in total 211 km of 45,456 roadways [5]. In Cape Breton Island, Highway 105 connects the gateway of the island (Canso Causeway) located in Port Hawkesbury to Sydney. Port Hawkesbury has been shown in **Figure 2**.

According to a research by MariNova Consulting Ltd. [7], total annual volumes of truck traffic at two locations in Cape Breton Island were 50,759 units through Hay Cove (St. Peter's) and 221,825 units through South Haven (Baddeck) in 2014. MariNova Consulting Ltd. [7] also pointed out that all rail users indicated that the conversion from rail to truck movements would be a factor of 1:3, which means 500 inbound carloads by rail in 2014 would convert to 1500 truckloads traveling between Port Hawkesbury and Sydney.

Most of the Sydney-area shippers transport the products by rail to Port Hawkesbury and use transloading at the Port Hawkesbury Paper (PHP) facility before completing the journey to Sydney by Truck. The transloading process would also increase shipping costs for the shippers. It would also be necessary for shippers to increase their capital costs and for PHP to improve their storage capacity [7].

For the area of Cape Breton Island, short haul trucking is available for both trailer loads and bulk shipping. In the research of MariNova Consulting Ltd. [7], some of the interviewees said that they are either using RST Industries (Irving Group) or Trimac to move resin from Moncton or Port Hawkesbury to Sydney. Another firm used Atlantic Diversified Trucking System (ADTS) flatbeds to transport products from Port Hawkesbury to Sydney. **Figure 3** illustrates the roads surrounding the Sydney area.

2.3. Rail

The Cape Breton and Central Nova Scotia Railway (CBNS) is the operator of a 245-mile short line railway between Truro and Sydney, with spurs at Stellarton, Point Tupper, and Sydney. This railway was primarily purchased by RailTex company in 1993, then RailAmerica company in 2000, and now it is owned by Genesee & Wyoming Inc. (G & W). The Sydney Subdivision, a portion of the overall Truro to Sydney line, comprises a 98-mile section between St. Peter's Junction (at Point Tupper) and Sydney [7]. A part of the railway across Sydney River has been shown in **Figure 4**.

The railway was active regularly over the past years. According to a study conducted in 2003, there were 520 outbound carloads of cargo per year originating east of St. Peter's. These carloads included transportation of some products such as steel, coal, logs, and scrap. There were 767 carloads of building supplies, scrap, bulk cement, petroleum products, resins, feed, logs, and intermodal cargo inbound at the same time [7].

Recently, traffic on the rail line has decreased. It had decreased to about 500 carloads in total by 2014, which led to the owners applying to the Nova Scotia Public Utilities and Review Board (UARB) to stop the rail service. Based on the estimates from Genesee & Wyoming,

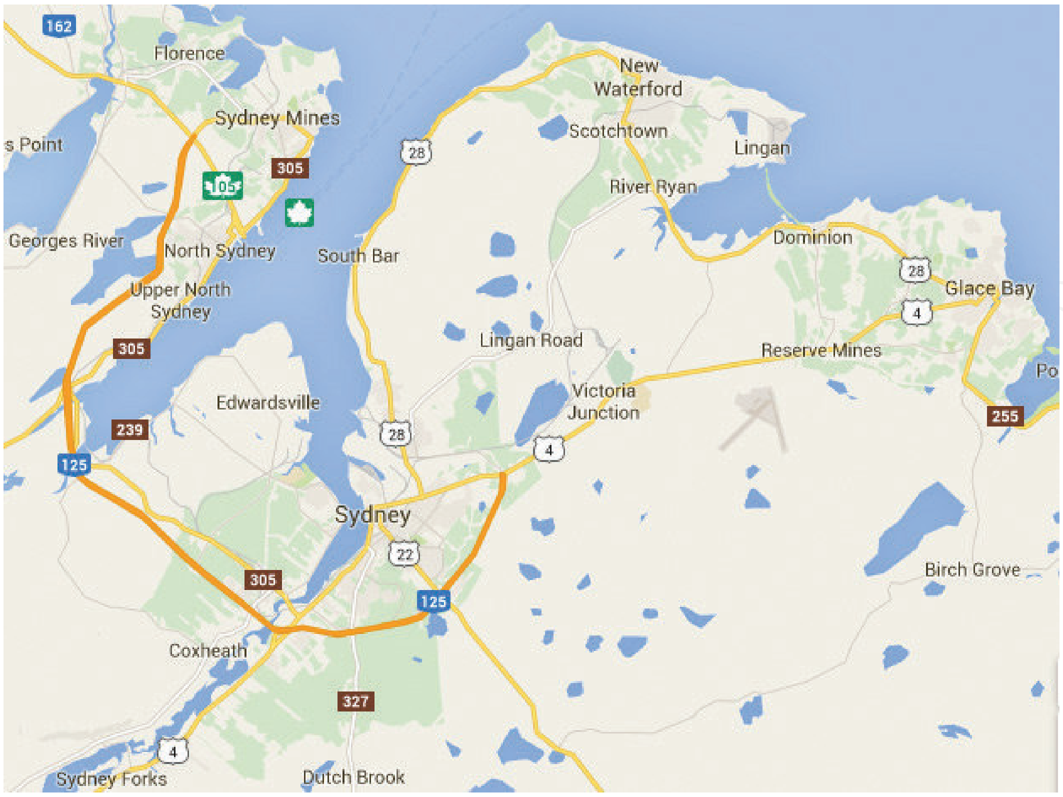

Figure 3. Roads connect Sydney Mines, North Sydney, Sydney, Glace Bay (source: Google Maps).

Figure 4. Railway across Sydney river in Cape Breton Island.

10,000 return carloads per year is the breakeven point for the Sydney Subdivision. For the past 10 years, losses resulting from reduced traffic volume were offset by an annual subsidy from the Province of Nova Scotia [7]. The owner did not resubmit the application for a $3 million yearly government subsidy in 2015, and the railway between Port Hawkesbury and Sydney was to be abandoned based on the authorization of the Nova Scotia regulator in October 2015 [26].

Due to the shut-down of this section of CBNS railway, some manufacturers would encounter challenges related to transportation costs. They would have to try and find new ways to receive raw materials [26]. It is expected that the businesses engaged in the transshipment of building supplies destined for Newfoundland and Labrador, and the businesses involved in feeding grain to the Island, and transportation of round wood (logs) would be affected significantly by the shut-down of the rail line [7].

2.4. Water

The Port of Sydney is situated on the East Coast of Canada. It is noticeable that it is the closest port in North America to the Suez Canal, Middle East, and India, as well as Europe. Its channel and sheltered inner harbor have the potential to handle the world's largest ships and vessels and the Port is placed on direct shipping routes to Europe, the U.S., Asia, and South America. The routes have been illustrated in **Figure 5**. In addition, the Port of Sydney is noted as the "Gateway to the Great Lakes" and is the furthest point that lake freighters or "lakers" can go during the 3 months of the year when the St. Lawrence cannot be voyaged [5].

Some studies show that the development of the port and related supply chains has a very good future and can provide more opportunities for the area. Insufficient investment in transportation infrastructure is the main challenge for the port development plan. It has been announced that Harbor-Port Development Partners (HPDP) have signed an agreement with one of the world's famous port construction companies, China Communications Construction Company Limited (CCCC) for the design, construction, and ownership of a deep-water container terminal in Sydney. The goal is not only to build the terminal, but also to bring business opportunities for all of the area's supply chain components [27]. As for the design and construction of Sydney's container terminal, CCCC plans to take charge of all required infrastructures and related equipment [28].

Marine Atlantic Inc. plays a significant role in water transportation through Cape Breton Island. The company provides ferry services between the island of Newfoundland and the Province of Nova Scotia over two routes; the routes are shown in **Figure 6**. The first route is a year-round, 96 nautical mile daily ferry service between North Sydney, Nova Scotia, and Port aux Basques located in Newfoundland and Labrador. The second one is active from mid-June until late September because of the weather conditions. It is a 280 nautical mile tri-weekly ferry service between North Sydney, Nova Scotia, and Argentia in Newfoundland and Labrador. The company provides service to more than 300,000 people yearly with 6–8 h travel between North Sydney and Port aux Basques, and 14–16 h travel between North Sydney and Argentia. Besides these routes, it also carries more than 100,000 commercial units each year, of which more than 50% of all products are being transported to and from the Newfoundland Island. Recently, there is a competition between the area and Halifax to transport the products needed to Newfoundland and Labrador.

Figure 5. The potential routes for water transportation to Cape Breton Island through Suez Canal (sources: Google Maps, website of Novaporte).

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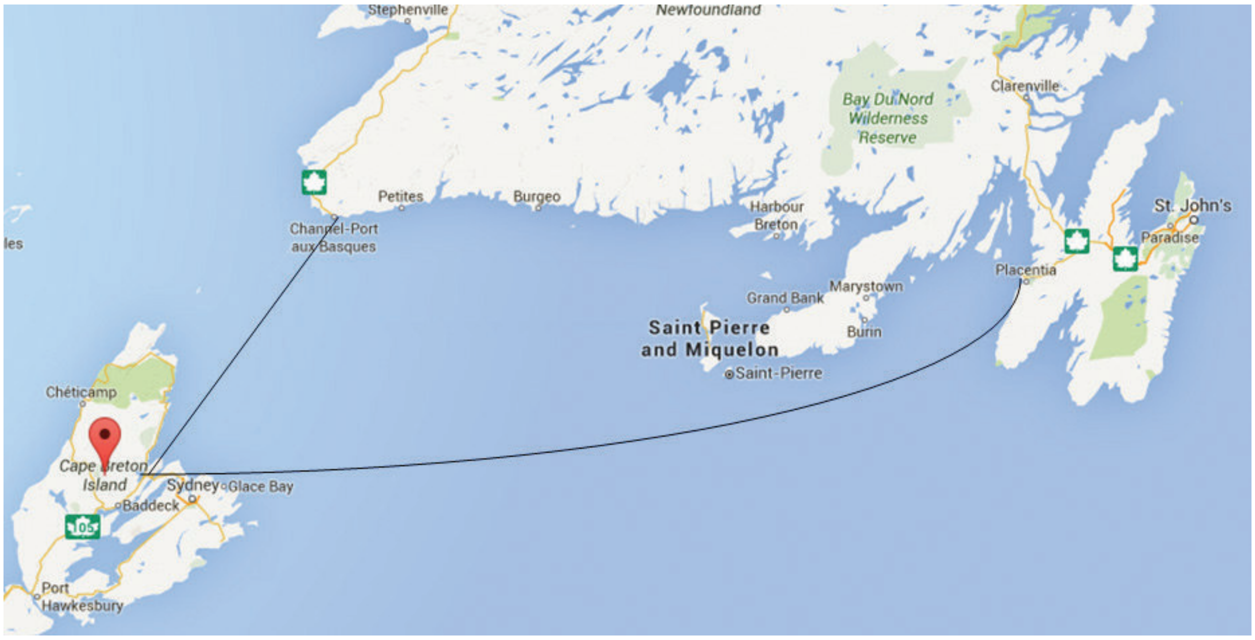

Figure 6. Water transportation from Cape Breton Island to Newfoundland and Labrador (source: Google Maps).

2.5. Intermodal

Truck transportation provides convenience to shippers in Cape Breton Island and has the ability to cooperate with other transportation modes well due to the highways, road conditions, and the flexibility of truck transportation. Especially after discontinue of rail way service, truck services gradually replace the role of rail service in Cape Breton Island. Port Hawkesbury, as the entrance of the Island from the (mainland) rest of Nova Scotia, plays a significant role in the development of the transportation aspect of Cape Breton Island.

Truck and water transportation modes in the Port of Sydney can be combined to promote the intermodal transportation of Cape Breton Island. This port is the gateway for all trucked cargo to and from Newfoundland and Labrador. Due to the condition of the highways, a full range of trucking services can provide an alternative to rail and water transportation modes.

There is a possibility of combining water and rail transportations in this area as well. The Cape Breton and Central Nova Scotia Railway (CBNS) has discussed with HPDP recently about the possibility of providing future rail service on the line from Truro to Sydney, as a part of the deep water port development project in Sydney [28].

3. SWOT matrix

SWOT analysis is one of the most straightforward approaches that can be used in the analysis of a company's strategic position. It includes factors of internal strengths and weaknesses, as well as external opportunities and threats [10, 14].

We propose the following steps to analyze transportation modes of areas and regions:

Step 1: identifying the SWOT factors: brainstorming, SWOT form, interview, and literature review can be applied to identify strengths, weaknesses, opportunities, and threats factors.

Step 2: ranking the factors: multifactor process and pairwise comparisons are utilized to rank the identified factors.

Step 3: calculating the average of the weights for each factor: the results of Step 2 are combined to obtain the average of the weights for each factor.

Step 4: transportation strategies: transportation strategies related to the identified strengths, weaknesses, opportunities, and threats in the region are defined by the experts.

In this section, we apply these steps to analyze the transportation modes in Cape Breton Island.

3.1. Identifying the factors

In this research, we have applied four methods including brainstorming, SWOT form, interview, and literature review to identify the SWOT factors. (i) Brainstorming: we discussed and analyzed the potential SWOT factors in group meetings. Each group included 4 or 5 people. At the beginning of each session, we provided some general information about the transportation modes using PowerPoint slides. We emphasized that this research focuses on business transportation, not public transportation. (ii) SWOT form: **Table 2** shows SWOT form that has been designed based on tables of Rauch [29] and Rauch et al. [14]. In addition to this table, we have provided an example of a SWOT table adopted from Dadvar et al. [16]. The example was helpful to provide ideas for the people. (iii) Interview: we noticed that it is a challenging task for some individuals to fill out the SWOT form. As a result, we conducted some interviews to find SWOT factors. The goal was to explore views and ideas related to this research. (iv) Literature review: some publications about transportation modes in the area have been mentioned in Section 1.1. We reviewed those publications to find the SWOT factors. The identified SWOT factors have been written in **Table 3**. In addition, SWOT factors based on transportation modes have been illustrated in **Figure 7**.

Internal strengths	**Internal weaknesses**
What are the advantages of the transportation modes in the area? What is done well? What do others see as advantages of them?	What are the current disadvantages of the transportation modes in the area? What could be done better? What is actually done poorly?
- Shipping between the area and Newfoundland and Labrador	- Lack of rail services
External opportunities	**External threats**
Which trends are affecting the transportation modes in the area? Which opportunities can arise from these trends?	Are there any relevant future competition scenarios? What are possible barriers and relevant changes? Does a technology shift or a change in legal framework threaten the actual status?
- Port of Sydney development plan	- Competition between the area and Halifax

Table 2. SWOT form.

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Strengths	Weaknesses
Air	Air
S1: Passenger and cargo services through Sydney airport	W1: Small scale of Sydney Airport
Rail	W2: Limitations in flight destinations
S2: Existence of railways	W3: High cost of passenger and freight transportations
Truck	W4: Infrequent flight schedules
S3: Several roads and highways	Rail
S4: Operations of local companies with economies of scale	W5: Lack of rail services
S5: Shipping of fresh and flash frozen seafood products by refrigerated trucks to USA	W6: High cost of upgrading railways and related infrastructures
Water	Truck
S6: Shipping between the area, and Newfoundland and Labrador	W7: Existence of one connection road to the mainland
S7: Ice free Sydney harbor	W8: All roads and highways are not twin
S8: Existence of cruise	W9: Poor highways maintenance
S9: Geographical location of Port of Sydney	W10: Fresh food deliveries from Halifax to the area is limited in each week
S10: One of the deepest harbors in North America	Water
S11: Fully operational and well developed shipping pier	W11: Lack of governance on port of Sydney and lack of cooperation between municipality and senior governments
S12: Existence of greenfield site which is ready for port of Sydney development	W12: Different ownerships of Sydney harbor bottom
Intermodal	W13: Cruise berth limitations in Port of Sydney
S13: Land availability for projects development	Intermodal
S14: Tourism transportation	W14: Poor public transportation options to the Halifax
Opportunities	**Threats**
Air	Rail
O1: Future development in the Sydney airport	T1: Lack of information sharing about the importance of railways in the community
O2: Future development in Margaree and Port Hawkesbury airports to reach tourism destinations	Truck
O3: Increased flights and better schedules	T2: Poor highway maintenance continues to reduce number of privately-operated tour bus services
Rail	T3: Competition between local transportation companies and other companies
O4: The possibility of buying and maintaining rails by external companies	Water
O5: Future rail services	T4: Competition between the area and Halifax

Strengths	Weaknesses
Truck	Intermodal
O6: Standards improvement of highway construction to lengthen lifespan of road surfaces	T5: Decreasing trend in population of the area
Water	T6: Weather conditions such as storm
O7: Port of Sydney development plan	T7: Increase in the cost of fuel for motor vehicles and marine vessels
O8: Relocating ice breakers to the port of Sydney	T8: Short-term limitations because of stricter emission standards and environmental issues
Intermodal	T9: Poor economic conditions impacting transportation development
O9: Potential transportation businesses related to Donkin coal mine	T10: Limitations of government funding and support for development of transportation modes
O10: Shipment from larger vessels to smaller vessels in port of Sydney	T11: Older demographic in local areas
O11: Technological innovations	T12: Policy of provincial government for infrastructure development in Halifax area and Sydney area
O12: Growth of tourism industry in the region	T13: Limited high-speed internet outside municipal population clusters that limits economic development opportunities
O13: New markets and businesses due to increased transportation modes	
O14: Cost saving and less damages to the roads due to the existence of the rails	

Table 3. SWOT factors.

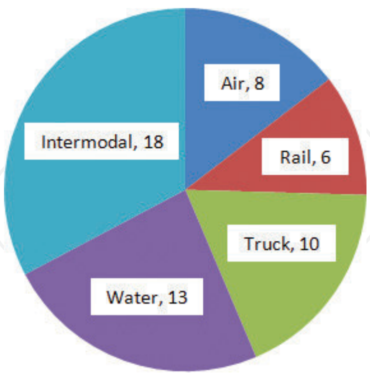

Figure 7. SWOT factors based on transportation modes.

3.2. Ranking the factors

In this section, the five most important factors from each group (strengths, weaknesses, opportunities, and threats) are selected and ranked. Two methods including multifactor process and pairwise comparisons are utilized to rank the SWOT factors. Then, the results are compared.

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3.2.1. Multifactor process

In the multifactor decision-making process, 3 experts (E_1, E_2, E_3) assign scores for each SWOT factor. The scale includes 1–9 in which 9 means extremely important. Then, the numbers are combined and the averages and ranks are calculated. The results have been written in **Table 4**. Based on the rankings, "Geographical location of Port of Sydney," "Lack of governance on port of Sydney and lack of cooperation between municipality and senior governments," "Port of Sydney development plan," and "Poor economic conditions impacting transportation development" are the main transportation factors in the area.

3.2.2. Pairwise comparisons

Some studies have shown that pairwise comparisons can provide more reliable results than the multifactor process [30–32]. Pairwise comparisons are utilized in analytic hierarchy process (AHP) [30]. We used a scale that ranges from equally preferred to extremely preferred (1—equally preferred, 2—equally to moderately preferred, 3—moderately preferred, 4—moderately to strongly preferred, 5—strongly preferred; 6—strongly to very strongly preferred; 7—very strongly preferred; 8—very to extremely strongly preferred; 9—extremely preferred). **Table 5** shows the results of the comparisons for strengths assigned by Expert 1. For example, the expert determines that S3 is moderately preferred to S2. Thus, she assigns 3.

In pairwise comparisons method, we should check the consistency vector. Interested readers can refer to [31] for more information. Generally, the consistency ratio should be 0.10 or less. Otherwise, the results are not consistent and the expert should fill the tables again [31]. In this case, the results are consistent.

Strengths	**E_1**	**E_2**	**E_3**	**Average**	**Rank**	**Weaknesses**	**E_1**	**E_2**	**E_3**	**Average**	**Rank**
S2	7	3	6	5.33	3	W3	7	7	6	6.66	2
S3	8	5	8	7	2	W5	8	4	7	6.33	3
S6	6	5	5	5.33	3	W6	6	2	6	4.66	5
S9	8	7	7	7.33	1	W9	6	2	7	5	4
S10	7	9	5	7	2	W11	6	7	8	7	1
Opportunities	**E_1**	**E_2**	**E_3**	**Average**	**Rank**	**Threats**	**E_1**	**E_2**	**E_3**	**Average**	**Rank**
O3	6	6	6	6	3	T4	6	5	5	5.33	5
O5	8	2	6	5.33	4	T5	7	3	8	6	3
O6	6	4	8	6	3	T6	9	2	6	5.66	4
O7	8	8	8	8	1	T9	7	8	7	7.33	1
O12	7	8	7	7.33	2	T10	6	7	8	7	2

Table 4. SWOT ranking based on multifactor process.

Strengths	S2	S3	S6	S9	S10
S2	1	1/3	2	1/3	1/2
S3	3	1	2	2	3
S6	0.5	1/2	1	1/3	2
S9	3	1/2	3	1	2
S10	2	1/3	1/2	1/2	1
Column totals	9.5	2.67	8.5	4.16	8.5

Table 5. Pairwise comparisons by E_1 strengths.

The process is repeated and the numbers are obtained based on the opinions of 3 experts (E_1, E_2, and E_3) for other factors. The weights and the ranks have been written in **Table 6**. All consistency ratios are less than 0.10.

3.2.3. *Calculating the average of the weights for each factor*

There are some differences between the ranks of the factors in **Tables 4** and **6**. Pairwise comparisons method is preferred to multifactor process method when we do not feel confident or comfortable about determining the factor weights independently. In this paper, we calculate the average of the weights of two methods (normalized multi factor process and pairwise comparisons). The results have been written in **Table 7**. Most of the ranks are like **Table 8**. We observe that "Several roads and highways," "Port of Sydney development plan," "Lack of governance on port of Sydney and lack of cooperation between municipality and senior governments,", and "Poor economic conditions impacting transportation development" are the main transportation factors in the region.

Strengths	E_1	E_2	E_3	Average	Rank	Weaknesses	E_1	E_2	E_3	Average	Rank
S2	0.12	0.04	0.19	0.117	5	W3	0.07	0.38	0.12	0.190	2
S3	0.35	0.11	0.43	0.297	1	W5	0.37	0.12	0.26	0.250	1
S6	0.13	0.13	0.15	0.137	4	W6	0.21	0.06	0.26	0.177	3
S9	0.27	0.22	0.12	0.203	3	W9	0.14	0.06	0.19	0.130	4
S10	0.13	0.5	0.12	0.250	2	W11	0.20	0.38	0.17	0.250	1
Opportunities	E_1	E_2	E_3	**Average**	**Rank**	**Threats**	E_1	E_2	E_3	**Average**	**Rank**
O3	0.07	0.16	0.11	0.113	4	T4	0.12	0.14	0.19	0.150	4
O5	0.22	0.05	0.31	0.193	3	T5	0.36	0.08	0.31	0.250	2
O6	0.09	0.11	0.12	0.107	5	T6	0.22	0.07	0.13	0.140	5
O7	0.49	0.34	0.31	0.380	1	T9	0.21	0.41	0.19	0.270	1
O12	0.14	0.34	0.15	0.210	2	T10	0.09	0.28	0.17	0.180	3

Table 6. SWOT ranking based on pairwise comparisons.

Strengths	M	P	Average	Rank	Weaknesses	M	P	Average	Rank
S2	0.167	0.117	0.142	5	W3	0.225	0.190	0.207	3
S3	0.219	0.297	0.258	1	W5	0.213	0.250	0.232	2
S6	0.167	0.137	0.152	4	W6	0.157	0.177	0.167	4
S9	0.229	0.203	0.216	3	W9	0.169	0.130	0.149	5
S10	0.219	0.250	0.234	2	W11	0.236	0.250	0.243	1
Opportunities	**M**	**P**	**Average**	**Rank**	**Threats**	**M**	**P**	**Average**	**Rank**
O3	0.184	0.113	0.149	4	T4	0.170	0.150	0.160	4
O5	0.163	0.193	0.178	3	T5	0.192	0.250	0.221	2
O6	0.184	0.107	0.145	5	T6	0.181	0.140	0.160	4
O7	0.245	0.380	0.312	1	T9	0.234	0.270	0.252	1
O12	0.224	0.210	0.217	2	T10	0.223	0.180	0.202	3

Table 7. SWOT ranking based on combination of normalized multifactor process (M) and pairwise comparisons (P) methods.

Modes	Strategies	Related SWOT factors	Rank
Air	Improve flights schedules and develop air cargo businesses	O3, O12, W3, T5, T6	5
Rail	Increase the activities that lead to have the rail services	S2, S6, O5, W5, W6, T5	4
Water	Focus on port of Sydney development plan	S9, S10, O7, W11, T10	1
Truck	Improve the road conditions and develop new roads	S3, S6, O6, W9, T5, T10	3
Intermodal	Increase the investment in different modes of transportations	S6, O12, T4, T10	2

Table 8. Transportation strategies.

4. Transportation strategies

The three experts were invited to think about the transportation strategies related to the identified strengths, weaknesses, opportunities, and threats in the region. **Table 8** shows the five main transportation strategies that are suggested by them. The work of Andrews [33] made the idea popular that a good strategy means ensuring a fit between the external situation a firm faces and its own internal qualities or characteristics. The proposed strategies have some characteristics connecting them to the SWOT factors. The experts have determined the related SWOT factors. We utilize and combine the weights of the SWOT factors (**Table 7**) to find the overall weight of each strategy and find the ranks in **Table 8**. Based on the information given in **Table 8**, "Focus on port of Sydney development plan" is the most important transportation strategy for the area (Rank 1).

5. Conclusions

In this chapter, we have provided a summary of transportation modes (air, truck, rail, water, and intermodal) in Cape Breton Island. The summary is helpful to provide insight for future applied transportation projects in the area. Furthermore, we have identified SWOT factors including strengths, weaknesses, opportunities, and threats in the region. This chapter is the first investigation that has identified the SWOT factors related to transportation modes in the area. We have selected 20 factors (out of 55) and have ranked them using two methods (multi-factor process, and pairwise comparisons). Then, we have compared and combined the results. Three experts contributed in this process. Based on our analysis, the most important transportation elements in Cape Breton Island are "Several roads and highways," "Port of Sydney development plan," "Lack of governance on port of Sydney and lack of cooperation between municipality and senior governments," and "Poor economic conditions impacting transportation development". Finally, the appropriate transportation strategies have been discussed. This paper provides the steps to analyze transportation characteristics of any area or region.

In this chapter, the SWOT factors have been identified and ranked by the experts. It is valuable to consider uncertainty in this process by using different methods such as fuzzy sets theory and compare the results. In addition, analytic network process (ANP) can be applied in future investigations to rank the factors. ANP is a decision-making technique which structures the problem as a network.

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Multi-Echelon Data Envelopment Analysis Variable Returns to Scale Models for Performance Evaluation of Supply Chains

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Additional information is available at the end of the chapter

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Abstract

This paper develops a variable returns to scale multi-echelon data envelopment analysis (DEA) model to measure the efficiency of supply chain. The model is constructed at first with the assumption of serial sequence in a supply chain. The inputs of one stage become the output of the other stage in the multi-echelon structure. The traditional variable returns to scale model of DEA is modified to fit in the multi-echelon structure. The developed model helps to evaluate the supply network in a coordinated manner. It also provides helpful insights as how to improve the supply network performance.

Keywords: DEA, variable returns to scale, supply chain, process cycles

1. Introduction

Supply chain is a coordinated system of various processes meshed together to form a network of strategic decision making. All the stages in supply chain are connected together through feed-forward flow of materials and services as well as feedback flow of information [1]. Several studies in the literature have underlined the practical importance of supply-chain performance measures. Gunasekaran and Patel [2] argue that frequent evaluation and benchmarking of supply chain outputs are necessary for companies to achieve their supply chain management (SCM) objectives. Supply chain measures are crucial for the coordination of cross-functional and inter-organizational activities in SCM, and for forming long-term alliances among firms in the chain [3, 4]. Performance evaluation of supply chain helps to improve processes and coordinate efforts of different stages and make contracting and risk sharing feasible in a supply chain. However, detailed analysis of processes in a supply chain is a time and resource consuming process [5]. To improve supply chain performance it is imperative to measure it. With the measurement of performance the symptoms of the problem in a supply chain can be identified. After identifying the symptoms managers can focus on detailed activity analysis at an operational level.

Bibliography of [6] reveals that there is dearth of literature that utilized mathematical programming and associated statistical techniques to help decision making in supply chain benchmarking. Reference [7] reveals most models whether deterministic or stochastic deals with single player in a supply chain rather than considering supply chain as a system. There are some issues in measuring the efficiency of supply chain. The first point is the involvement of different stages of supply chain to contain the DEA model. Secondly, the improvement projection has to be coordinated at all stages of supply network.

New methods have been developed to measure the supply chain performance using DEA. For instance, Ref. [8] decomposes the traditional DEA model to product of efficiencies by decomposing the overall efficiency score. Reference [9] also decomposes the overall efficiency scores of multiplicative efficiency model using game theory concepts. Reference [10] presents a model to decompose overall radial efficiency of supply network at additive weighted average of all the individual stages of supply chain network. In many cases, DMUs may have internal or network structures; see for example, [11–13]. The types of special DMUs have inputs converted to outputs and vice versa in the intermediate stages. Recently, some of the studies have modeled DEA in two-stage processes. For example, Ref. [14] divides the US commercial banks into profitability and marketability as first stage and second stage respectively. For the first stage, they use labour and assets as inputs and profits and revenues and outputs. In the second stage, the output in the first stage, i.e., profit and revenue are used as inputs and market value, returns and earning per share constitute output. Reference [8] uses the same method of two stage process for non-insurance companies where they use operating and insurance expenses as outputs in the first stage and then underwriting and investment profits in the second stage. Other examples include the impact of information technology use on bank branch performance [15], two stage Major League Baseball performance [16], and many others.

In this paper, we use multi-echelon variable returns to scale Data Envelopment Analysis (DEA) to measure performance of supply chain. In traditional DEA, the internal structures are generally ignored, the efficiency score is a function of given inputs and outputs [17]. More specifically, the production capability of production units is formulated only under some general assumptions.[1] The advantage of DEA is that utilizing multiple inputs and outputs it gives a single index for measurement.

Although there are certain advantages of DEA, however, when dealing with supply chain it becomes a limitation. Therefore, the DEA model needs to be modified appropriately to contain the different connecting stages of supply chain to act as a single DMU. Further, DEA has an assumption that the stages of supply chain are independent and not connected which clearly violated the coordination nature of supply chain. In this paper, we have modeled

[1]These assumptions on the production function include: monotonicity, convexity, envelopment and minimum extrapolation; see [18] for an explanation.

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the multi-echelon variable returns to scale DEA in such a way that the coordination property of supply chain is retained.

There is a substantial body of DEA literature, however, the use of DEA in supply chain network to evaluate performance is limited. Reference [19] proposes a DEA model using value chain approach to measure the performance of supply chain stages; Ref. [15] use the value-chain model to evaluate IT's impact on firm performance. References [7] and [20] propose efficiency evaluation approaches for a two-tier supply chain model from a game theoretic perspective. [12, 21, 22] introduce the network DEA model, in which the interior structure of production units can be explicitly modeled. These studies tend to view supply chains as a sequence of static, but independent processes. Reference [8] described a two-stage process where 24 non-life insurance companies used operating and insurance expenses to generate premiums in the first stage and then underwriting and investment profits in the second stage. Other articles in this general area are due to [9, 10, 16]. Reference [23] suggests that performance measures should be systematically deployed in a top-down fashion to ensure the organization is controllable and well coordinated. A significant body of work has been directed at problem settings where the DMU is characterized by a multi-stage process; supply chains and many manufacturing processes take this form [24–26]. Supply chains similarly need a systematic structure of performance measures for different units, e.g., individual firms, tiers in the supply chain, and the whole chain.

DEA models are classified with respect to the type of envelopment surface, the efficiency measurement and the orientation (input or output). There are two basic types of envelopment surfaces in DEA known as constant returns-to-scale (CRS) and variable returns-to-scale (VRS) surfaces. Each model makes implicit assumptions concerning returns-to-scale associated with each type of surface. Charnes et al. [17] introduced the CCR or CRS model that assumes that the increase of outputs is proportional to the increase of inputs at any scale of operation [27]. Banker et al. [28] introduced the BCC or VRS model allowing the production technology to exhibit increasing returns-to-scale (IRS) and decreasing returns-to-scale (DRS) as well as CRS. All the mentioned papers of recent literature has examined a particular form of network structure, namely, where the DMU is a two-stage serial process in which the outputs from the first stage are intermediate variables that serve as inputs to the second stage. The current article extends this idea to include those situations where the overall process can be decomposed into product of the efficiencies of four processes. Therefore, we propose two models of efficiency decomposition that deals with the assumption of variable returns to scale (VRS).

The rest of the paper is organized as follows. In Section 2, we propose two models of efficiency decomposition namely, multi-echelon VRS model and multi-echelon VRS additive model. The proposed models assume variable returns to scale (VRS). In Section 3, we discuss model application. Finally our conclusions are presented in Section 4.

2. Multi-echelon DEA models

It is important to note that traditional DEA models assume that the operations follow constant returns to scale. This represented one of the most limiting factors for the applicability of DEA, at least in the early years. Many economists viewed this assumption as over-restrictive and preferred alternative statistical procedures in spite of the advantage offered by DEA.

Modifications of DEA to handle VRS categories were first described in 1984, when [28] came up with a simple yet remarkable modification to the CCR DEA models in order to handle variable returns to scale. This modification was suggested by comparing some previous studies on production functions. Hence, the DEA model is termed BCC (Banker, Charnes, Cooper) model. In general, DEA programs incorporating an additional convexity constraint to take into account variable returns to scale are called variable returns to scale or VRS model.

2.1. Multi-echelon variable returns to scale model

Consider the c-cycle process pictured in **Figure 1**. Suppose we have n DMUs and that each $DMU_j (j = 1, 2, \ldots, n)$ has m inputs to first stage, and S outputs from this stage, z_{sj_o}, $s = 1, 2, .., S$. These S outputs then become the inputs to the second cycle and Z_{op_o}, where $o = 0, 1, \ldots, O$, is the input or enters as a input of the existing stage and other subsequent stages. The outputs from second, third and fourth stages are denoted as yr_{j_o} where $r = 1, 2, \ldots, R$, v_{lj_o}, where $l = 1, 2, \ldots, L$ and w_{kg_o} where $g = 1, 2, \ldots, G$. The weights of cycle 1, cycle 2, cycle 3, and cycle 4 are η_S^A, u_r, μ_l, and γ_k. The input weights of stage 1, 2, 3, and 4 are v_i, v_{op}, w_{op}, and O_{op}. The VRS efficiency score for the four stages can be determined by the following VRS models [28]:

$$\theta^* = Max \frac{\sum_{s=1}^{S} \eta_s^A z_{sj_o}}{\sum_{i=1}^{m} v_i x_{ij_o}} \cdot \frac{\sum_{r=1}^{R} u_r y_{rj_o}}{\left(\sum_{s=1}^{S} \eta_s^A z_{sj_o} + \sum_{p=1}^{P} v_{op_o} z_{op_o}\right)} \cdot \frac{\sum_{l=1}^{L} \mu_l v_{lj_o}}{\sum_{r=1}^{R} u_r y_{rj_o} + \sum_{q=1}^{Q} w_{op} z_{op_o}} \cdot \frac{\sum_{g=1}^{G} \gamma_k w_{kj_o}}{\left(\sum_{l=1}^{L} \mu_l v_{lj_o} + \sum_{n=1}^{N} o_{op} z_{op_o}\right)} \tag{1}$$

subject to,

$$\frac{\sum_{s=1}^{S} \eta_s^A z_{sj_o}}{\sum_{m=1}^{m} v_i x_{ij_o}} \leq 1 \tag{2}$$

$$\frac{\sum_{r=1}^{R} u_r y_{rj_o}}{\sum_{s=1}^{S} \eta_S^A z_{sj_o} + \sum_{p=1}^{P} v_{op} z_{op_o}} \leq 1 \tag{3}$$

$$\frac{\sum_{l=1}^{L} \mu_l v_{lj_o}}{\sum_{r=1}^{R} u_r y_{rj_o} + \sum_{q=1}^{Q} w_{op} z_{op_o}} \leq 1 \tag{4}$$

$$\frac{\sum_{g=1}^{G} \gamma_k w_{kj_o}}{\sum_{l=1}^{L} \mu_l v_{lj_o} + \sum_{n=1}^{N} o_{op} z_{op_o}} \leq 1 \tag{5}$$

$$\sum_{s=1}^{S} \eta_s^A + \sum_{r=1}^{R} u_r + \sum_{l=1}^{L} \mu_l + \sum_{g=1}^{G} \gamma_k = 1 \tag{6}$$

$$\eta_s^A, v_i, u_r, v_{op_o}, \mu_l, w_{op}, \gamma_k, o_{op} \geq 0$$

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Using Charnes-Cooper transformation [29], Eqs. (1)–(5) are equivalent to,

$$Max\left[\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}\right)\cdot\left(\sum_{r=1}^{R}u_r y_{rj_o}\right)\cdot\left(\sum_{l=1}^{L}\mu_l v_{lj_o}\right)\cdot\sum_{g=1}^{G}\gamma_k w_{kj_o}\right]$$

subject to,

$$\left(\sum_{i=1}^{m}v_i x_{ij_o}\right)\cdot\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}+\sum_{p=1}^{P}v_{op_o}z_{op_o}\right)\cdot\sum_{r=1}^{R}u_r y_{rj_o}+\sum_{q=1}^{Q}w_{op}z_{op_o}\cdot \left(\sum_{l=1}^{L}\mu_l v_{lj_o}+\sum_{n=1}^{N}o_{op}z_{op_o}\right)=1 \quad (7)$$

$$\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}\right)-\left(\sum_{i=1}^{m}v_i x_{ij_o}\right)\leq 1 \quad (8)$$

$$\left(\sum_{r=1}^{R}u_r y_{rj_o}\right)-\left(\sum_{s=1}^{S}\eta_S^A z_{sj_o}+\sum_{p=1}^{P}v_{op}z_{op_o}\right)\leq 1 \quad (9)$$

$$\left(\sum_{l=1}^{L}\mu_l v_{lj_o}\right)-\left(\sum_{r=1}^{R}u_r y_{rj_o}+\sum_{q=1}^{Q}w_{op}z_{op_o}\right)\leq 1 \quad (10)$$

$$\left(\sum_{g=1}^{G}\gamma_k w_{kj_o}\right)-\left(\sum_{l=1}^{L}\mu_l v_{lj_o}+\sum_{n=1}^{N}o_{op}z_{op_o}\right)\leq 1 \quad (11)$$

$$\sum_{s=1}^{S}\eta_s^A+\sum_{r=1}^{R}u_r+\sum_{l=1}^{L}\mu_l+\sum_{g=1}^{G}\gamma_k=1 \quad (12)$$

$$\eta_s^A, v_i, u_r, v_{op_o}, \mu_l, w_{op}, \gamma_k, o_{op}\geq 0$$

A scale efficiency score of less than one does not indicate whether the organization is bigger or smaller than its optimal size. To establish this, an additional variant of DEA, one subject to non-increasing returns to scale must be run. The DEA linear programming problem for the non-increasing returns to scale case is given by:

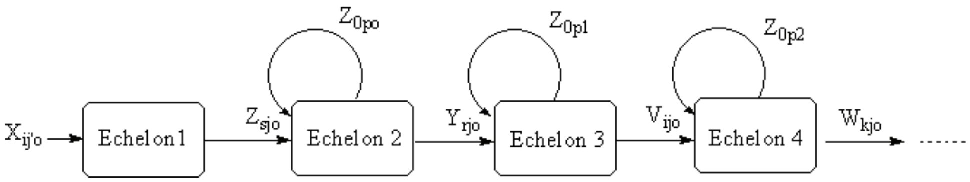

Figure 1. A serial multi-echelon DEA with inputs, *carryover inputs*, and outputs.

$$Max\left[\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}\right)\cdot\left(\sum_{r=1}^{R}u_r y_{rj_o}\right)\cdot\left(\sum_{l=1}^{L}\mu_l v_{lj_o}\right)\cdot\sum_{g=1}^{G}\gamma_k w_{kj_o}\right]$$

subject to,

$$\left(\sum_{i=1}^{m}v_i x_{ij_o}\right)\cdot\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}+\sum_{p=1}^{P}v_{op_o}z_{op_o}\right)\cdot\sum_{r=1}^{R}u_r y_{rj_o}+\sum_{q=1}^{Q}w_{op}z_{op_o}\cdot \left(\sum_{l=1}^{L}\mu_l v_{lj_o}+\sum_{n=1}^{N}o_{op}z_{op_o}\right)=1 \tag{13}$$

$$\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}\right)-\left(\sum_{i=1}^{m}v_i x_{ij_o}\right)\leq 1 \tag{14}$$

$$\left(\sum_{r=1}^{R}u_r y_{rj_o}\right)-\left(\sum_{s=1}^{S}\eta_S^A z_{sj_o}+\sum_{p=1}^{P}v_{op}z_{op_o}\right)\leq 1 \tag{15}$$

$$\left(\sum_{l=1}^{L}\mu_l v_{lj_o}\right)-\left(\sum_{r=1}^{R}u_r y_{rj_o}+\sum_{q=1}^{Q}w_{op}z_{op_o}\right)\leq 1 \tag{16}$$

$$\left(\sum_{g=1}^{G}\gamma_k w_{kj_o}\right)-\left(\sum_{l=1}^{L}\mu_l v_{lj_o}+\sum_{n=1}^{N}o_{op}z_{op_o}\right)\leq 1 \tag{17}$$

$$\sum_{s=1}^{S}\eta_s^A+\sum_{r=1}^{R}u_r+\sum_{l=1}^{L}\mu_l+\sum_{g=1}^{G}\gamma_k\leq 1 \tag{18}$$

$$\eta_s^A, v_i, u_r, v_{op_o}, \mu_l, w_{op}, \gamma_k, o_{op}\geq 0$$

2.1.1. Multi-echelon VRS additive model

We let $\sum_{i=1}^{m}v_i x_{ij_o}+\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}+\sum_{p=1}^{P}v_{op_o}z_{op_o}\right)+\left(\sum_{r=1}^{R}u_r y_{rj_o}+\sum_{q=1}^{Q}w_{op}z_{op_o}\right)+\left(\sum_{l=1}^{L}\mu_l v_{lj_o}+\right.$ $\left.\sum_{n=1}^{N}o_{op}z_{op_o}\right)=|R|$ represent the total amount of resources consumed by the four-cycle process. The model 1–5 with incorporation of variables ψ^A, ψ^B, ψ^C, and ψ^D becomes

$$Max\left[\frac{\sum_{s=1}^{S}\eta_s^A z_{sj_o+\psi^A}+\sum_{r=1}^{R}u_r y_{rj_o+\psi^B}+\sum_{l=1}^{L}\mu_l v_{lj_o+\psi^C}+\sum_{g=1}^{G}\gamma_k w_{kj_o}+\psi^D}{|R|}\right] \tag{19}$$

subject to,

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$$\frac{\sum_{s=1}^{S}\eta_s^A z_{sj_o} + \psi^A}{\sum_{i=1}^{m} v_i x_{ij_o}} \leq 1 \tag{20}$$

$$\frac{\sum_{r=1}^{R} u_r y_{rj_o} + \psi^B}{\sum_{s=1}^{S}\eta_S^A z_{sj_o} + \sum_{s=1}^{S} v_{op} z_{op_o}} \leq 1 \tag{21}$$

$$\frac{\sum_{l=1}^{L} \mu_l v_{lj_o} + \psi^C}{\sum_{r=1}^{R} u_r y_{rj_o} + \sum_{q=1}^{Q} w_{op} z_{op_o}} \leq 1 \tag{22}$$

$$\frac{\sum_{g=1}^{G} \gamma_k w_{kj_o} + \psi^D}{\sum_{l=1}^{L} \mu_l v_{lj_o} + \sum_{n=1}^{N} o_{op} z_{op_o}} \leq 1 \tag{23}$$

$$\psi^A, \psi^B, \psi^C, \text{ and } \psi^D, \text{ free in sign.}$$

$$\eta_s^A, v_i, u_r, v_{op_o}, \mu_l, w_{op}, \gamma_k, o_{op} \geq 0, \quad j_o, \quad p_o = 1, 2, \dots, n.$$

Model (19)–(23) is equivalent to

$$Max\left[\sum_{s=1}^{S}\eta_s^A z_{sj_o} + \psi 1 + \sum_{r=1}^{R} u_r y_{rj_o} + \psi 2 + \sum_{l=1}^{L} \mu_l v_{lj_o} + \psi 3 + \sum_{g=1}^{G} \gamma_k w_{kj_o} + \psi 4\right] \tag{24}$$

subject to,

$$\left(\sum_{s=1}^{S}\eta_s^A z_{sj_o}\right) - \left(\sum_{i=1}^{m} v_i x_{ij_o} + \psi^1\right) \leq 0 \tag{25}$$

$$\left(\sum_{r=1}^{R} u_r y_{rj_o}\right) - \left(\sum_{s=1}^{S}\eta_S^A z_{sj_o} + \sum_{p=1}^{P} v_{op} z_{op_o} + \psi^2\right) \leq 0 \tag{26}$$

$$\left(\sum_{l=1}^{L} \mu_l v_{lj_o}\right) - \left(\sum_{r=1}^{R} u_r y_{rj_o} + \sum_{q=1}^{Q} w_{op} z_{op_o} + \psi^3\right) \leq 0 \tag{27}$$

$$\left(\sum_{g=1}^{G} \gamma_k w_{kj_o}\right) - \left(\sum_{l=1}^{L} \mu_l v_{lj_o} + \sum_{n=1}^{N} o_{op} z_{op_o} + \psi^4\right) \leq 0 \tag{28}$$

$$|R| = 1 \tag{29}$$

$$\psi^1, \psi^2, \psi^3, \text{ and } \psi^4, \text{ free in sign.}$$

$$\eta_s^A, v_i, u_r, v_{op_o}, \mu_l, w_{op}, \gamma_k, o_{op} \geq 0$$

3. Application

A supply chain consists of all parties involved directly or indirectly in fulfilling a customer request. The supply chain includes not only the manufacturers and suppliers, but also transporters, warehouses, retailers and even customers themselves. A supply chain is a series of processes and can be described as cycle view. A cycle view of supply chain divides processes into cycles each performed at the interface between two successive stages of a supply chain [30].

The cycle view of process is important as it delineates the responsibilities of each player of each stage. The process cycle helps making operational decision as it clearly mentions the roles and responsibilities of each member of the supply chain. To evaluate the performance of supply chain we consider the four cycles namely—customer cycle, replenishment cycle, manufacturing cycle and procurement cycle. The first cycle, i.e., the customer cycle starts at the retailer's site. The customer fills in the demand and the demand is received by the retailer. The cycle initiates as soon as the retailer receives the order from the customer.

From the customer cycle we take two inputs - Technological functionality and Sales order by FTE. The first input is the functionality of the technology in place. This is measured in units of functionality where a higher number indicates more functionality. The second input is sales order by full time employee (FTE). This indicator measures the number of customer orders that are processed by full time employees per day. The outputs for customer cycle are Order fulfillment cycle time and Cycle inventory. Order fulfillment cycle time is a continuous measurement defined as the amount of time from customer authorization of a sales order to the customer receipt of product. On the other hand, Cycle inventory represents the average order quantity amount on hand. The inputs and outputs extracted from customer cycle is displayed in **Table 1**.

The *replenishment cycle* [30] starts at the juncture of retailer or distributor interface and includes replenishing retailer inventory. The replenishment policy consist of decisions regarding when to reorder and how much to reorder. The decisions determine the cycle and safety inventory. The inputs of replenishment cycle are—technological functionality and sales order by FTE. The first input is the functionality of the technology in place. This is measured in units of

Customer order cycle	Description
Inputs	
Technological functionality	The functionality of the technology in place. This is measured in units of functionality where a higher number indicates more functionality
Sales order by FTE	This indicator measures the number of customer orders that are processed by full time employees per day.
Outputs	
Order fulfillment cycle time	It is a continuous measurement defined as the amount of time from customer authorization of a sales order to the customer receipt of product
Cycle inventory	It represents the average order quantity amount on hand

Table 1. Inputs and outputs of customer cycle.

functionality where a higher number indicates more functionality. The second input is sales order by full time employee (FTE). This indicator measures the number of customer orders that are processed by full time employees per day. The outputs of replenishment cycle are—Fill rate, Inventory cycle time and Cycle inventory. Fill rate is the number of items ordered compared with items shipped. Fill rate can be calculated on a line item, SKU, case or value basis. Inventory cycle time is a measure of the Manufacturing Cycle Time plus the time included to deploy the product to the appropriate distribution center and Cycle inventory represents the average order quantity amount on hand. The inputs and outputs of replenishment cycle are given in **Table 2**.

The *manufacturing cycle* [30] occurs at the distributor/manufacturer (or retailer/manufacturer) interface and includes all processes involved in replenishing retailer inventory. The manufacturing cycle is triggered by customer orders/replenishment orders/forecast of customer demand and current product availability in the manufacturer's finished goods warehouse.

The inputs of manufacturing cycle are—Bill-of-materials (BOM), Usage quantity and Independent demand ratio. Bill-of-materials (BOM) is a record of all the components of an item, the parent-component relationships, and the usage quantities derived from engineering and process design. Usage quantity is the number of units of a component needed to make one unit of its immediate parent. Independent demand ratio is for manufacturers that also supply replacement parts and consumables this metric helps to define the percentage mix of demand for an item from independent (outside sources) vs. dependent (inside sources). The ratio is calculated by dividing the unit usage for customer orders by the total unit usage of the item from all sources (work orders, sales samples, destructive testing, inventory adjustments, etc.). The outputs of manufacturing cycle are—Finished product cycle time and End item. Finished product cycle time is the average time associated with finalizing activities, such as: package, stock, etc. and the other output End item is the final product sold to a customer. The inputs and outputs of manufacturing cycle are displayed in **Table 3**.

Replenishment process cycle	Description
Inputs	
Technological functionality	The functionality of the technology in place. This is measured in units of functionality where a higher number indicates more functionality
Sales order by FTE	This indicator measures the number of customer orders that are processed by full time employees per day.
Outputs	
Fill rate	The number of items ordered compared with items shipped. Fill rate can be calculated on a line item, SKU, case or value basis.
Inventory cycle time	Measure of the Manufacturing Cycle Time plus the time included to deploy the product to the appropriate distribution center
Cycle inventory	It represents the average order quantity amount on hand.

Table 2. Inputs and outputs of replenishment cycle.

Manufacturing cycle	Description
Inputs	
Bill-of-materials (BOM)	A record of all the components of an item, the parent-component relationships, and the usage quantities derived from engineering and process design.
Usage quantity	The number of units of a component needed to make one unit of its immediate parent.
Independent demand ratio	For manufacturers that also supply replacement parts and consumables this metric helps to define the percentage mix of demand for an item from independent (outside sources) vs. dependent (inside sources). The ratio is calculated by dividing the unit usage for customer orders by the total unit usage of the item from all sources (work orders, sales samples, destructive testing, inventory adjustments, etc.).
Outputs	
Finished product cycle time	Average time associated with finalizing activities, such as: package, stock, etc.
End item	The final product sold to a customer.

Table 3. Inputs and outputs of manufacturing cycle.

The *procurement cycle* [30] takes place at the interface of manufacturer/supplier and includes the necessary processes to make sure that the materials are available for manufacturing to take place as per schedule. In the procurement cycle, the components are ordered by manufacturer from the suppliers that replenish the component inventory. In this cycle components are ordered precisely once the production set up is finalized by the manufacturer.

The inputs from the procurement cycle are - Purchased item and Direct material cost. Purchased item is an item that has one or more parents, but no components because it comes from a supplier. Direct material cost is the sum of costs associated with acquisition of support material. The outputs of procurement cycle are - On time ship rate and Delivery schedule adherence. On time ship rate is the percent of orders where shipped on or before the requested ship date. On time ship rate can be calculated on a line item, SKU, case or value basis. Delivery schedule adherence is a business metric used to calculate the timeliness of deliveries from suppliers. Delivery schedule adherence is calculated by dividing the number of on time deliveries in a period by the total number of deliveries made. The result is then multiplied by 100 and expressed as a percentage. The inputs and outputs of procurement cycle are displayed in **Table 4**.

3.1. Multi-echelon VRS DEA model results

The efficiency results of the CCR and BCC model are shown in **Table 5** for 11 supply chain sub-processes of a particular product (e.g., detergent). First, the efficient supply chains, in each process cycle are: customer order cycle (1, 4, 7, 9, and 11) replenishment process cycle (1, 2, 5, 6, 8, 11), manufacturing process cycle (2, 4, 6) and procurement process cycle (5, 6, 9). The same table shows the efficiency results of RTS. The RTS efficiency score is calculated as the ratio of CCR efficiency score to BCC efficiency score. **Table 5** indicates that, customer order cycle, the BCC efficient but not scale-efficient process, cycles were operating on an increasing returns to scale (IRS) frontier because they can achieve greater economies of scale if they increase the

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Procurement process cycle	Description
Inputs	
Purchased item	An item that has one or more parents, but no components because it comes from a supplier.
Direct material cost	Sum of costs associated with acquisition of support material.
Outputs	
On time ship rate	Percent of orders where shipped on or before the requested ship date. On time ship rate can be calculated on a line item, SKU, case or value basis.
Delivery schedule adherence	Delivery Schedule adherence (DSA) is a business metric used to calculate the timeliness of deliveries from suppliers. Delivery schedule adherence is calculated by dividing the number of on time deliveries in a period by the total number of deliveries made. The result is then multiplied by 100 and expressed as a percentage.

Table 4. Inputs and outputs of procurement process cycle.

DMU	Customer cycle			Replenishment cycle			Manufacturing cycle			Procurement cycle			Efficiency	
	CCR[1]	BCC[2]	RTS[3]	CCR	BCC	RTS	CCR	BCC	RTS	CCR	BCC	RTS	CCR	BCC
1	1.00	1.00	CRS	1.00	1.00	CRS	0.08	0.19	DRS	0.63	0.98	DRS	0.677	0.792
2	1.00	1.00	CRS	1.00	1.00	CRS	1.00	1.00	CRS	1.00	1.00	CRS	1.000	1.000
3	0.45	0.49	DRS	0.76	0.82	IRS	0.06	0.09	DRS	0.17	0.18	IRS	0.360	0.395
4	1.00	1.00	CRS	0.45	0.61	IRS	0.46	1.00	DRS	0.64	0.92	DRS	0.637	0.882
5	0.51	0.54	IRS	1.00	1.00	CRS	0.13	0.39	DRS	0.44	1.00	DRS	0.520	0.732
6	0.43	1.00	IRS	0.66	1.00	IRS	0.27	1.00	IRS	0.64	1.00	DRS	0.500	1.000
7	0.97	1.00	DRS	0.69	0.70	DRS	0.02	0.03	DRS	0.12	0.12	IRS	0.450	0.462
8	0.52	0.53	IRS	1.00	1.00	CRS	0.10	0.10	CRS	0.28	0.30	IRS	0.475	0.482
9	0.90	1.00	IRS	0.45	0.95	IRS	0.43	0.75	DRS	1.00	1.00	CRS	0.695	0.925
10	0.74	0.94	DRS	1.00	1.00	CRS	0.01	0.02	IRS	0.09	0.11	IRS	0.460	0.517
11	0.76	1.00	DRS	0.96	1.00	DRS	0.01	0.02	IRS	0.06	0.07	IRS	0.447	0.522

[1]Charnes-Cooper-Rhodes Model.
[2]Banker-Charnes-Cooper Model.
[3]Returns-to-Scale.

Table 5. Multi-echelon VRS model results of supply chains.

volume. For customer order cycle, five BCC-efficient retail chains were operating on IRS and four on decreasing returns to scale (DRS) frontiers. Of the BCC-inefficient supply chains, 64% and 20% were in the IRS region in cycle 1 and cycle 2, respectively. As economists have long recognized, an IRS frontier firm would generally be in a more favorable position for expansion, compared to a firm operating in a DRS region. Note that the concept of RTS may be ambiguous unless a process cycle is on the BCC-efficient frontier, since we classified RTS for inefficient process cycles by their input oriented BCC projections. Thus, a different RTS classification may be obtained for a different orientation, since the input-oriented and the output-oriented BCC models can yield different projection points on the VRS frontier. Thus, it is necessary to explore the robustness of the RTS classification under the output oriented DEA method. Note that an IRS DMU (under the output-oriented DEA method) must be termed as IRS by the input oriented DEA method. Therefore, one only needs to check the CRS and DRS supply chain processes in the current study. Using the input oriented approach, we discover only two DRS supply chain processes in replenishment cycle (DMUs 2, 4, 6 and 9) and seven DRS (DMUs 1, 3, 4, 5, 6, 7, and 9) in the manufacturing cycle. These results indicate that (i) in general; the RTS classification under different process cycle is independent of the orientation of DEA model; and (ii) there are serious input deficiencies in manufacturing cycle at the current usage quantities derived from engineering and process design. Given the fact that supply chains are assigned different efficiencies in case of CRS and VRS assumptions, i.e., using CCR models and BCC models, we can distinguish two different kinds of efficiencies Technical and Scale Efficiencies. The CCR model (without the convexity constraint) estimates the gross efficiency of a supply chain. This efficiency comprises technical efficiency and scale efficiency. Technical efficiency describes the efficiency in converting inputs to outputs, while scale efficiency recognizes that economy of scale cannot be attained at all scales of production, and that there is one most productive scale size, where the scale efficiency is maximum at 100%. The multi-stage VRS model takes into account the variation of efficiency with respect to the scale of operation, and hence measures pure Technical Efficiency. Note that while only DMU 2 is assigned 100% efficiency in the case of the CRS assumption, DMU 6 is considered 100% efficient in case of the VRS assumption. This indicates that the inefficiencies assigned to DMU 2 in case of the CRS assumption are purely due to their scales of operation.

Although a number of observations on supply chain cycles are efficient, only one supply chain performance (DMU 2) is efficient, i.e., the observation 2 represents the best practice of the supply chain system. Note that, all the supply chain cycles are efficient. Note that individual supply chain process efficiency is greater than the overall supply chain efficiency score, indicating that supply chain system could achieve more input savings.

Model 24 yields optimal values on the performance measures for supply chain to reach the best practice. Consider DMU 4 in **Table 5**. Since customer order cycle is efficient, no adjustments for measures related to the customer cycle are required. However, in order to reach the best practice, the replenishment, manufacturing, and procurement cycles should reduce their direct input. In addition, the procurement and manufacturing cycles should reach an agreement on the procurement price of raw materials to increase the revenue of procurement cycle. The fill rate of replenishment cycle should be increased. This solution indicates that based upon the best practice, the replenishment cycle should be able to maintain a fill rate of 90% while the manufacture reduces its shipment to the distributor of replenishment cycle.

Some supply chains may choose to operate with high cost and high availability while others are lean with lower levels of service. The notion of DEA efficiency provides an approach for efficiency measurement of supply chain and its processes. Multi-echelon VRS DEA models makes it clear that two supply chains may have different input-output mix yet both may be efficient. This model enables supply chain processes to collectively improve the supply chain performance. Through the use of the proposed models, any supply chains can find ways to achieve best-practice performance and to gain competitive edge.

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4. Conclusion

Recent literature has examined a particular form of network structure, namely, where the DMU is a two-stage serial process in which the outputs from the first stage are intermediate variables that serve as inputs to the second stage. The current article extends this idea to include those situations where the overall process can be decomposed into product of the efficiencies of four stages. Therefore, we propose two models of efficiency decomposition that deals with the assumption of variable returns to scale (VRS). The proposed models, i.e., multi-stage DEA variable returns to scale (VRS) models that we have developed, adopt an alternative view of efficiency decomposition four-echelon supply chain structure. Our approach extends and generalizes the [8] and [10] two-stage models to four-echelon supply chain model with inclusion of the supply chain process concept in using inputs and outputs.

The analysis of the process cycles of 11 supply chains using the proposed DEA models shows that close to 45% of the supply chains were inefficient in four process cycles namely—customer order cycle, replenishment process cycle, manufacturing cycle and procurement cycle. Further, most supply chains exhibited DRS in manufacturing cycle and procurement cycle, while some of them exhibited IRS in customer order cycle and replenishment process cycle. This suggests that up-stream components of the supply chain may have a negative effect on finished product cycle time and end item.

We developed the multi-stage DEA models to evaluate the efficiency of supply chains. In these models, firms' production processes in multi-stages are interrelated. The empirical application shows that using conventional DEA models could lead to significantly biased evaluation results in multi-stage production situations. We also show that breaking down the production processes of supply networks for evaluation can generate more practical insights in how to improve the supply network performance, either in terms of technical or scale efficiencies.

The multi-echelon DEA models developed in this paper can be applied to a wide range of practical situations, including evaluating the effect of investments in IT systems and environmental improvements, human resources and the pollution effect etc. Future studies can deal with evaluating panel and longitudinal performance and efficiency changes of firms (e.g., [31–33]). The multi-stage DEA model can benefit these studies by providing a more accurate estimation of firms' performance over time. In the multi-stage DEA models the assumption of sequential flow of inputs and outputs may be relaxed to give rise to a complex model that can best fit the real world scenario.

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Chapter 5

Two-Phase Network Data Envelopment Analysis: An Example of Bank Performance Assessment

Yu-cheng Liu

Additional information is available at the end of the chapter

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Abstract

Data envelopment analysis (DEA) models assess decision-making units (DMUs), which directly convert multiple inputs into multiple outputs. Network DEA models have been studied extensively. However, the performance indices that link the two stages are assumed to be fixed or non-discretionary; their values are not adjustable. These models only assumed that the reductions on the inputs and additions on the outputs would improve the overall efficiency. But in the real world, the link is always adjustable. "Free links" means that the intermediate items are adjustable or discretionary, and each DMU can be increased or decreased from the observed one. The current chapter introduces a two-phase procedure with free links to assess system performance, Phase-I is a proposed slack-based measurement (SBM) model to partition the links into two sets: as-input and as-output. Phase-II is a modified SBM model to determine the slack of each input, as-input link, output and as-output link. This proposed model counts the slacks associated with the intermediate items in the efficiency scores and determines the entire system performance by the directional distance function. It is validated using network procedure and assesses the performance of supply chain management system.

Keywords: data envelopment analysis, performance measure, directional distance function, network DEA, slack-based measure

1. Introduction

The data envelopment analysis (DEA) models assess a set of homogeneous decision-making units (DMUs) that convert inputs into outputs. Fewer input values and more output values are desired and DMUs may be classified as being either efficient or inefficient. Tone and Tsutsui [1, 2] introduce network and dynamic DEA and categorize links into two types—"fixed links" and “free links”. The free links mean the links are adjustable; each DMU can be increased or decreased from the observed one and identifies the improvement target of each inefficient DMU on the frontier that is constructed by the efficient DMUs.

Seiford and Zhu [3] and Zhu [4] have introduced a two-stage process to measure the profitability and marketability of 55 US commercial banks and top Fortune 500 companies, respectively. They propose the effect of bank size on profitability and marketability through evaluating both technical and scale efficiencies. Sexton and Lewis [5] use a two-stage approach to evaluate the scores of American Major League Baseball teams. There are many other cases in which the whole operation is separated into more than two processes. These may have a series structure, a parallel structure, or a mixture of these. These structures are generally called network structures and the DEA technique to measure the efficiency of systems with a network structure is called network DEA (Färe & Grosskopf [6]). Färe and Whittaker [7] and Färe and Grosskopf [8] introduce models to compute the efficiency scores of sub-processes in network-structured DEA problems. Lewis and Sexton [9] introduce a network DEA model which focuses efficiency-enhancing strategies on individual stages of the production process. Kao and Hwang [10] introduce a framework for breaking down the efficiency of the entire process into the product of the efficiencies of the two-stage process. It assumes that the weights on the links are the same for the two stages, that is, the weights on the outputs in the first stage are assumed to be equal to the weights on the inputs in the second stage. In the real world, the relative weight of each stage is determined corresponding to its importance. Thus, the different weights in the entire system are mentioned in recent studies. Chen et al. [11] mentions that the overall efficiency scores resulting from Kao and Hwang [10] are not direct indicators of potential input reductions or output increases not realized by the inefficient DMUs. They develop an approach to determine the DEA frontier or DEA projections for inefficient DMUs. Chen et al. [12] note that the envelopment-based network DEA model should be used for determining the frontier projection for inefficient DMUs, whereas the multiplier-based network DEA model should be used for determining the divisional efficiency because it does not account for the intermediate links. Kao [13] proposes a dynamic DEA model to measure system and period efficiencies at the same time for multi-period systems. Chang et al. [14] take into account the ownership structure of networks in constructing effective network DEA models and accordingly develop three ownership-specified (centralized, distributed, and hybrid) network DEA models. Huang et al. [15] proposed a two-stage network model with bad outputs and supper efficiency (US-NSBM). Empirical comparisons show that the US-NSBM may be promising and practical for taking the nonperforming loans into account and being able to rank all samples.

However, these approaches do not count the slacks associated with the intermediate items in the efficiency scores. Consequently, the efficiency scores are greater than the actual efficiency. In addition, there is no DMU with an efficiency score equal to 1 because the properties of intermediate performance evaluation items would lead to conflicts. For instance, in the two-stage process problem, Stage-2 may have to reduce inputs (links) to achieve an efficient status. However, doing so would lead to a reduction in outputs in Stage-1, thereby reducing the efficiency of Stage-1. In other words, there are still two efficiency frontiers for the two sub-processes. One may desire a single frontier for the entire production system.

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"Link" cannot be adjusted freely in a radial model which adjusts the inputs and outputs by the efficiency scores in a two-stage process. For this model, the entire system efficiency cannot be improved by adjusting links, see Kao and Hwang [10] and Lewis and Sexton [9]. "Link" that applies in a non-radial model has been discussed in recent years. Tone and Tsutsui [1] introduce a network DEA and categorize links into two types—"fixed links" and "free links." "Free links" means the intermediate items are adjustable or discretionary; each DMU can be increased or decreased from the observed one and is free to assign each individual link to one of the three characteristics: as-input, as-output, or non-discretionary so that the entire system efficiency could be maximized. "Fixed links" means the intermediate products are beyond the control of DMUs. In the radial model, "links" cannot be adjusted freely, which adjust the inputs and outputs by the efficiency scores in a two-stage process. Tone and Tsutsui [2] introduce the dynamic slack-based measure (DSBM) model and the incorporation of slacks with *free* and *fixed* links into the efficiency score. They categorize the links into four types: desirable, undesirable, discretionary (free), and non-discretionary (fixed). The article incorporates the slacks of free links into the efficiency score in two ways: an ex-post approach (adjusted score) and incorporation through 0–1 MIP. The ex-post approach includes a two-phase procedure. Tone and Tsutsui [1] introduce the links are discretionary regarding their status, as-input or as-output. Liu and Liu [16, 17] adopt VGM and GBM models to assess the performance of supply chain management.

Chambers et al. [18] introduced the directional distance function (DDF) based on the Luenberger benefit function to obtain the technical efficiency by increasing the outputs and reducing the inputs simultaneously. Later, Chambers et al. [19] introduced the DDF of DEA to measure the technical efficiency. This chapter develops a model for an improved efficiency measure through directional distance formulation of data envelopment analysis.

The contribution and innovative progress for this chapter are (1) creating a new SBM model and converting multi-efficiency frontiers for the separation processes to an aggregation efficiency frontier for the entire production system and (2) adopting free links application and introducing DDF with a virtual gap diagram to assess the performance of the entire system. The rest of this chapter is organized as follows. The proposed two-phase two-stage performance evaluation models and DDF are presented in Section 2. Because the uniqueness of the optimal solution is important, we report an experiment on this subject using a real-world bank performance assessment in Section 3. We conclude this chapter in the last section.

2. The proposed two-phase two-stage performance evaluation

J denotes the set of homogeneous decision-making units of a network process that are evaluated by a set of inputs, I, a set of free links, D^{free}, and a set of outputs R. DMU_o represents the DMU under evaluation. To maximize the system efficiency score of DMU_o, each link in set D^{free} is "free" to be assigned to one of the subsets – D_o^-, D_o^{free}, and D_o^+ if it is as-input, free link, and as-output, respectively. **Figure 1** depicts the two-phase procedure to evaluate the performance of DMUs using the two-stage and network processes. This two-phase procedure contains two

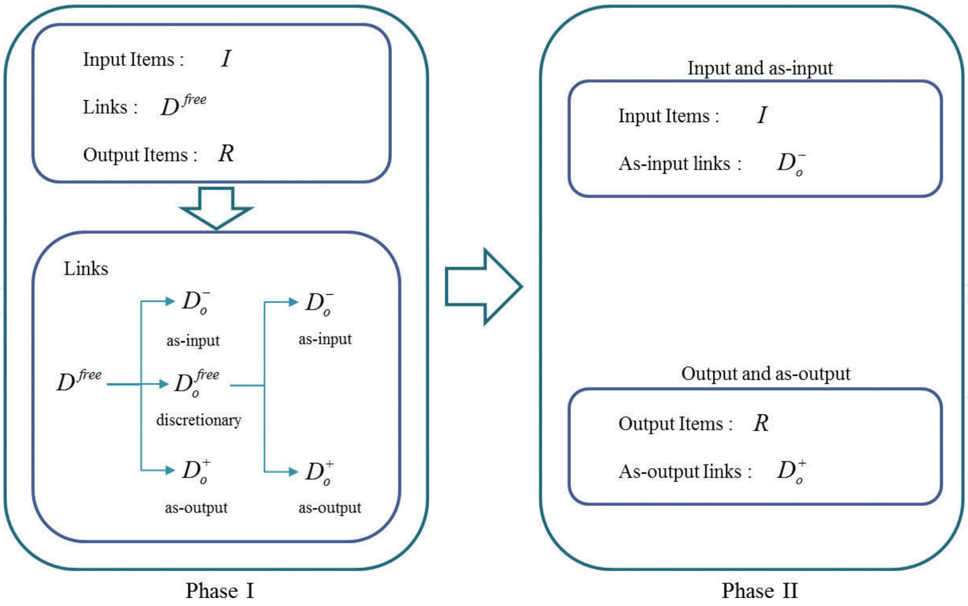

Figure 1. The flow of two-phase procedure.

slack-based DEA linear programming models. Phase-I sets all links in set D^{free} to discretionary and the objective is to determine the maximum slack values on each input and output so that the weights of each DMU in each stage can be assigned. The set D^{free} is partitioned into two subsets D_o^-, D_o^{free} and D_o^+. The output of Phase-I will indicate that several links in set D_o^{free} should be assigned to sets D_o^- and D_o^+. The target of Phase-II is thus to determine the maximum reduction value on each input and link in sets I and D_o^- and the addition value on each output and link in sets R and D_o^+ such that the weights of each DMU in the system can be assigned. The target of each input, free link, and output on the frontier is identified.

2.1. Two stages: Phase-I

Envelopment via the SBM fractional programming model [M1] is used to measure the relative performance of DMU_o. The decision variables of slack are the values to be subtracted at the ith input and the value to be added at the rth output, respectively. The decision variables denote the weights of DMU_j at Stage-1 and Stage-2, respectively. The right-hand side of constraints (1.2) and (1.3) expresses the targets of the inputs and links (outputs) at Stage-1. Each link d in set D^{free} is free to increase the slack s_{zd}^{free+} or decrease the slack s_{zd}^{free-}. These slacks are non-discretionary and not counted in the objective function. The decision variables on the left-hand side are $\lambda_{1j}, \ j \in J$. Similarly, the right-hand side of constraints (1.4) and (1.5) expresses the targets of the links (inputs) and outputs at Stage-2. The decision variables on the left-hand side are $\lambda_{2j}, \ j \in J$. Constraints (1.3) and (1.4) indicate that their right-hand sides are equal; each link d in set D^{free} can be freely adjusted to reach its single target at Stage-1 and Stage-2 simultaneously. The optimal slack value of link d in set D^{free}, $-s_{zd}^{free-*} + s_{zd}^{free+*}$, is >0, <0 or =0, in which case link d of DMU_o is assigned to sets D_o^+, D_o^-, and D_o^{free}, respectively. Two tasks remain for

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DMU_o. The first task is to assign all elements in the set to either D_o^+ or D_o^-. The second task is to place the slacks of link d in sets and add them to its aggregate performance score. Phase-II of our solving procedure addresses the first task.

[M1]

$$\rho_o^{(\mathrm{I})*} = \mathrm{Min}\left[1 - \left(\sum_{i\in I}\frac{s_i^-}{x_{io}}\right)/|I|\right]\bigg/\left[1 + \left(\sum_{r\in R}\frac{s_r^+}{y_{ro}}\right)\bigg/|R|\right]; \tag{1}$$

$$s.t. \quad \sum_{j\in J}\lambda_{1j}x_{ij} = x_{io} - s_i^-, \quad i\in I; \tag{2}$$

$$\sum_{j\in J}\lambda_{1j}z_{dj} = z_{do} + s_{zd}^{free+} - s_{zd}^{free-}, \quad d\in D^{free}; \tag{3}$$

$$\sum_{j\in J}\lambda_{2j}z_{dj} = z_{do} + s_{zd}^{free+} - s_{zd}^{free-}, \quad d\in D^{free}; \tag{4}$$

$$\sum_{j\in J}\lambda_{2j}y_{rj} = y_{ro} + s_r^+, \quad r\in R; \tag{5}$$

$$s_i^-, s_r^+, s_{zd}^{free+}, s_{zd}^{free-}, \lambda_{qj}\geq 0; \quad q = 1, 2; \quad j\in J; i\in I; \quad r\in R; \quad d\in D^{free}. \tag{6}$$

For the two-phase procedure which is depicted in **Figure 1**, Phase-I is to determine the maximum slack values on each input and output; [M1] presents this purpose and adopts Eq. (1.3) and (1.4) to distinguish links to be as-input, discretionary, and as-output, which express as three subsets, D_o^-, D_o^{free} and D_o^+, respectively. The aim of Phase-I is to assign each element in set D_o^{free} to either D_o^+ or D_o^-. [M2] is repeated until set D_o^{free} becomes empty. The fractional programming model [M2] measures the overall efficiency $\rho_o^{(\mathrm{II})*}$. The decision variables π_j^1 and π_j^2 denote the weights in Stage-1 and Stage-2, respectively, of DMU_j in evaluating DMU_o.

[M2]

$$\rho_o^{(\mathrm{II})*} = \mathrm{Min}\frac{\left(\sum_{i\in I}\frac{x_{io}-s_i^-}{x_{io}} + \sum_{d\in D_o^-}\frac{z_{do}-s_{zd}^-}{z_{do}}\right)\bigg/\left(|I| + |D_o^-|\right)}{\left(\sum_{r\in R}\frac{y_{ro}+s_r^+}{y_{ro}} + \sum_{d\in D_o^+}\frac{z_{do}+s_{zd}^+}{z_{do}}\right)\bigg/\left(|R| + |D_o^+|\right)}; \tag{7}$$

$$s.t. \quad \sum_{j\in J}\pi_j^1 x_{ij} = x_{io} - s_i^-, \quad i\in I; \tag{8}$$

$$\sum_{j\in J}\pi_j^1 z_{dj} = z_{do} - s_{zd}^-, \quad d\in D_o^-; \tag{9}$$

$$\sum_{j\in J}\pi_j^1 z_{dj} = z_{do} - s_{zd}^{free-} + s_{zd}^{free+}, \quad d\in D_o^{free}; \tag{10}$$

$$\sum_{j\in J}\pi_j^2 z_{dj} = z_{do} - s_{zd}^{free-} + s_{zd}^{free+}, \quad d\in D_o^{free}; \tag{11}$$

$$\sum_{j\in J}\pi_j^2 z_{dj} = z_{do} + s_{zd}^{+}, \quad d\in D_o^{+}; \tag{12}$$

$$\sum_{j\in J}\pi_j^2 y_{rj} = y_{ro} + s_r^{+}, \quad r\in R; \tag{13}$$

$$\pi_j^1, \pi_j^2 \geq 0,\ \ s_i^-, s_r^+ \geq 0,\ \ j\in J, i\in I,\ \ r\in R;\ \ s_{zd}^+ \geq 0,\ \ d\in D_o^+;\ \ s_{zd}^- \geq 0,\ \ d\in D_o^-. \tag{14}$$

$$s_{zd}^{free+}, s_{zd}^{free-} \geq 0,\ \ d\in D_o^{free}. \tag{15}$$

The solution of [M2] for each link d in set D_o^{free} is one of the following cases, $-s_{zd}^{free-*} + s_{zd}^{free+*} < 0$, $-s_{zd}^{free\ \ -*} + s_{zd}^{free+*} > 0$, and $-s_{zd}^{free-*} + s_{zd}^{free+*} = 0$. Next, d is assigned to set D_o^-, D_o^+, and D_o^{free} accordingly.

2.2. Two stages: Phase-II

The results of Phase-I indicate that DMU_o already partitioned set D_o^{free} into D_o^- and D_o^+. The fractional programming model [M3] is an SBM model (Tone and Tsutsui [21]) that measures the efficiency of converting the sets of input and as-input indices $I \cup D_o^-$ into the sets of output and as-output indices $R \cup D_o^+$. The frontiers of π_j^1 and π_{j}^2 are converted into an entire system frontier π_j in this phase.

[M3]

$$E_o^* = \text{Min}\frac{\left(\sum_{i\in I}\frac{x_{io}-s_i^-}{x_{io}} + \sum_{d\in D_o^-}\frac{z_{do}-s_{zd}^-}{z_{do}}\right)\Big/\left(|I| + |D_o^-|\right)}{\left(\sum_{r\in R}\frac{y_{ro}+s_r^+}{y_{ro}} + \sum_{d\in D_o^+}\frac{z_{do}+s_{zd}^+}{z_{do}}\right)\Big/\left(|R| + |D_o^+|\right)}; \tag{16}$$

$$s.t. \quad \sum_{j\in J}\pi_j x_{ij} = x_{io} - s_i^-, \quad i\in I; \tag{17}$$

$$\sum_{j\in J}\pi_j z_{dj} = z_{do} - s_{zd}^-, \quad d\in D_o^-; \tag{18}$$

$$\sum_{j\in J}\pi_j z_{dj} = z_{do} + s_{zd}^+, \quad d\in D_o^+; \tag{19}$$

$$\sum_{j\in J}\pi_j y_{rj} = y_{ro} + s_r^+, \quad r\in R; \tag{20}$$

$$\pi_j \geq 0, \ \ s_i^-, s_r^+ \geq 0, \ \ j\in J, i\in I, \ \ r\in R; \ \ s_{zd}^+ \geq 0, \ \ d\in D_o^+; \ \ s_{zd}^- \geq 0, \ \ d\in D_o^-. \tag{21}$$

The dual form of [M3] is expressed as [M4]. The decision variables of [M4] possess properties v_i and u_r, representing the weight assigned to the ith input and the rth output, respectively. The terms w_d^+ and w_d^- represent the weight assigned to link d in sets D_o^+ and D_o^-, respectively.

[M4]

$$\Delta_o^* = \text{Max}\left(-\sum_{i\in I} v_i x_{io} - \sum_{d\in D_o^-} w_d^- z_{do} + \sum_{d\in D_o^+} w_d^+ z_{do} + \sum_{r\in R} u_r y_{ro}\right); \tag{22}$$

$$s.t. \quad -\sum_{i\in I} v_i x_{ij} - \sum_{d\in D_o^-} w_d^- z_{dj} + \sum_{d\in D_o^+} w_d^+ z_{dj} + \sum_{r\in R} u_r y_{rj} \leq 0, \ \ j\in J; \tag{23}$$

$$v_i \geq (1/x_{io})/\left(|I| + \left|D_o^-\right|\right), \quad i\in I; \tag{24}$$

$$w_d^- \geq (1/z_{do})/\left(|I| + \left|D_o^-\right|\right), \quad d\in D_o^-; \tag{25}$$

$$w_d^+ \geq \varsigma \times (1/z_{do})/\left(|R| + \left|D_o^+\right|\right), \quad d\in D_o^+; \tag{26}$$

$$u_r \geq \varsigma \times \left(1/y_{ro}\right)/\left(|R| + \left|D_o^+\right|\right), \quad r\in R; \tag{27}$$

$$\varsigma = \left(1 - \sum_{i\in I} v_i x_{io} - \sum_{d\in D_o^-} z_{do} w_d^- + \sum_{d\in D_o^+} z_{do} w_d^+ + \sum_{r\in R} u_r y_{ro}\right); \tag{28}$$

$$v_i, u_r \text{ free in sign}, i\in I, \ \ r\in R; \tag{29}$$

$$w_d^- \ \text{ free in sign}, d\in D_o^-; w_d^+ \ \text{ free in sign}, d\in D_o^+. \tag{30}$$

Inequality (4.2) may be revised such that $\left(\sum_{r\in R} u_r y_{rj} + \sum_{d\in D_o^+} w_d^+ z_{dj}\right)\Big/\left(\sum_{i\in I} v_i x_{ij} + \sum_{d\in D_o^-} w_d^- z_{dj}\right) \leq 1$, and the constraint ensures that the maximum performance value of each DMU_j is not greater than 1.

2.3. Proposed directional distance function approach

The directional distance function (DDF) measures the distance from a certain operation point (e.g., DMU_o) to the efficient frontier of the technology along the positive semi-ray defined by vector g. Given a directional vector $g = \left(-g_X^-, g_Y^+\right)$, $g_X^- \in \mathfrak{R}_+^I \bigcup \mathfrak{R}_+^{D^-}$ and $g_Y^+ \in \mathfrak{R}_+^R \bigcup \mathfrak{R}_+^{D^+}$. The objective function (4.1) can be modeled by using the DDF. We denote virtual input by ($X = \sum_{i\in I} v_i x_{io} + \sum_{d\in D_o^-} w_d^- z_{do}$) and virtual output by ($Y = \sum_{d\in D_o^+} w_d^+ z_{do} + \sum_{r\in R} u_r y_{ro}$) which are identified by specifying a directional vector g. The objective function (4.1) can be converted to (4.9) which is to minimize the virtual input and maximize the virtual output to reach the efficient frontier.

$$\Delta_o^* = \text{Max}\left[\left(\sum_{i\in I} v_i x_{io} + \sum_{d\in D_o^-} w_d^- z_{do}\right)\left(-g_X^-\right) + \left(\sum_{d\in D_o^+} w_d^+ z_{do} + \sum_{r\in R} u_r y_{ro}\right)\left(-g_Y^+\right)\right]; \tag{31}$$

The graph technology can be represented by $T = \left\{(X, Y);\ X \in \mathfrak{R}_+^I \bigcap \mathfrak{R}_+^{D_o^-}, Y \in \mathfrak{R}_+^R \bigcap \mathfrak{R}_+^{D_o^+}\right\}$. The optimal solution of virtual gap Δ_o^* expresses as DDF: $\vec{D}_g\left(X, Y;\ -g_X^-, g_Y^+\right) = \sup\{\sum_{i\in I} x_{io} v_i^* \times \left(-g_X^-\right) + \sum_{d\in D_o^-} z_{do} w_d^{-*} \times \left(-g_X^-\right), \sum_{r\in R} y_{ro} u_r^* \times \left(g_Y^+\right) + \sum_{d\in D_o^+} z_{do} w_d^{+*} \times \left(g_Y^+\right) \in T(X, Y)\}$. This chapter defines a virtual gap diagram; the summation of input and as-input is the x-axis $\left(\sum_{i\in I} v_i x_{io} + \sum_{d\in D_o^-} w_d^- z_{do}\right)$ and the summation of output and as-output is the y-axis $\left(\sum_{d\in D_o^+} w_d^+ z_{do} + \sum_{r\in R} u_r y_{ro}\right)$. The geometry on the virtual gap diagram is the slope of the line from DMU_o to origin. To evaluate different DMU_o, one may directly compare their vectors of weights; virtual gap, Δ_o; virtual input and virtual as-input, Δ_o^I; and virtual as-output and virtual output, Δ_o^O. It is obvious that the minimum virtual gap "$\boldsymbol{\Delta_o^*}$" is equivalent to the maximum efficiency score of the entire network. It ensures that the nearest improvement target is found. **Figure 2** depicts the virtual gap diagram; x-axis denotes the virtual input and y-axis denotes the virtual output.

2.4. Overall stage efficiencies

Similar to the SBM non-oriented models of Tone and Tsutsui [20], the solutions of Phase-II provide a reference set of DMUs for DMU_o. The target for the performance items in sets I, D_o^+,

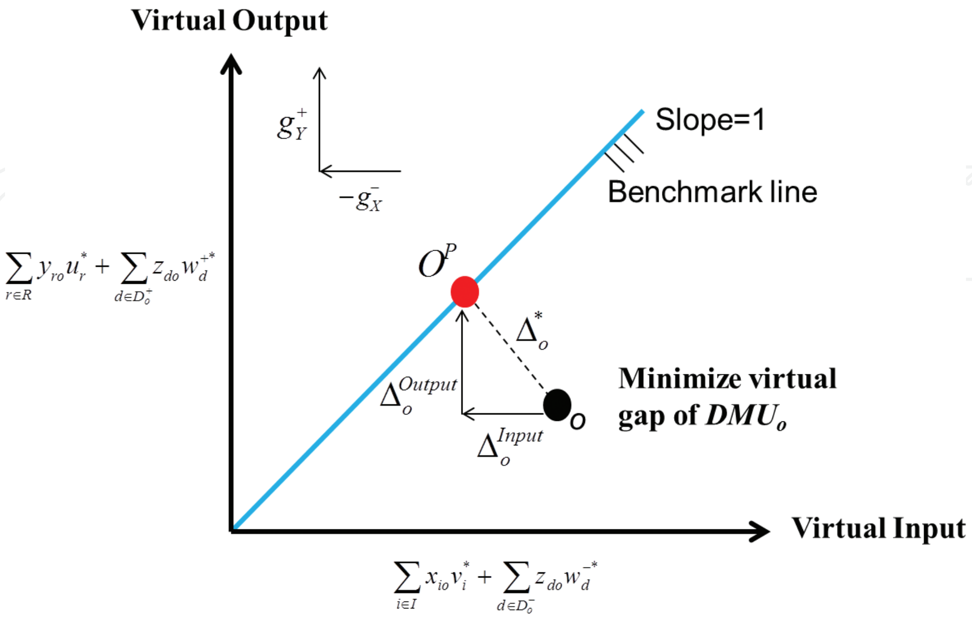

Figure 2. Virtual gap diagram.

D_o^-, and R can be obtained using [E1]. The measured performance value E_o^* is the best practice for DMU_o in the overall two-stage process which is expressed as [E2].

$$\begin{aligned} \widehat{x}_{io} &= x_{io} - s_i^{-*}, \quad i \in I; \\ \widehat{y}_{ro} &= y_{ro} + s_r^{+*}, \quad r \in R; \\ \widehat{z}_{do}^{+} &= z_{do} + s_{zd}^{+*}, \quad d \in D_o^+; \\ \widehat{z}_{do}^{-} &= z_{do} - s_{zd}^{-*}, \quad d \in D_o^-. \end{aligned} \tag{32}$$

These points are the projection of DMU_o on the frontier.

$$E_o^* = \frac{\left(\sum_{i \in I} \frac{\hat{x}_{io}}{x_{io}} + \sum_{d \in D_o^-} \frac{\hat{z}_{do}^-}{z_{do}}\right) \Big/ \left(|I| + |D_o^-|\right)}{\left(\sum_{r \in R} \frac{\hat{y}_{ro}}{y_{ro}} + \sum_{d \in D_o^+} \frac{\hat{z}_{do}^+}{z_{do}}\right) \Big/ \left(|R| + |D_o^+|\right)} \tag{33}$$

The results of Phase-II, $s_i^{-*}, s_{zd}^{-*}, s_{zd}^{+*}$ and s_r^{+*}, are used to compute the efficiencies of Stage-1, E_1^*, and Stage-2; E_2^* is shown in the following two Eqs. (E3 and E4). For the efficiencies of Stage-1, the numerator is the summation of inputs ($x_{io}, \ i \in I$) and as-input ($z_{do}, \ d \in D_o^-$). The denominator is the as-output items ($z_{do}, \ d \in D_o^+$). Likewise, for the efficiencies of Stage-2, the numerator is the as-input item ($z_{do}, \ d \in D_o^-$). The denominator is the summation of the as-output ($z_{do}, \ d \in D_o^+$) and outputs ($y_{ro}, \ r \in R$).

$$E_o^{*1} = \frac{\left(\sum_{i \in I} \frac{\hat{x}_{io}}{x_{io}} + \sum_{d \in D_o^-} \frac{\hat{z}_{do}^-}{z_{do}}\right) \Big/ \left(|I| + |D_o^-|\right)}{\sum_{d \in D_o^+} \frac{\hat{z}_{do}^+}{z_{do}} \Big/ |D_o^+|} \tag{34}$$

If set D_o^+ is empty, the denominator is equal to 1.

$$E_o^{*2} = \frac{\sum_{d \in D_o^-} \frac{\hat{z}_{do}^-}{z_{do}} \Big/ |D_o^-|}{\left(\sum_{r \in R} \frac{\hat{y}_{ro}}{y_{ro}} + \sum_{d \in D_o^+} \frac{\hat{z}_{do}^+}{z_{do}}\right) \Big/ \left(|R| + |D_o^+|\right)} \tag{35}$$

If set D_o^+ is empty, the numerator is equal to 1.

From Eqs. [E3] and [E4], we obtain the performance scores of Stage-1 and Stage-2, respectively, which identify the performance of each stage.

2.5. To extend two-stage to network process

Liu and Liu [16] extend the two-stage to network process. The network contains a set of sub-processes (nodes), H. The nodes are assigned ordinal numbers 1, 2, 3,…, n. Let A denote the set of network links. There are n homogeneous DMUs in set J, named DMU_1, DMU_2,…, and DMU_n, which are randomly processed by the sub-processes in set H. The network structure is depicted in **Figure 3**.

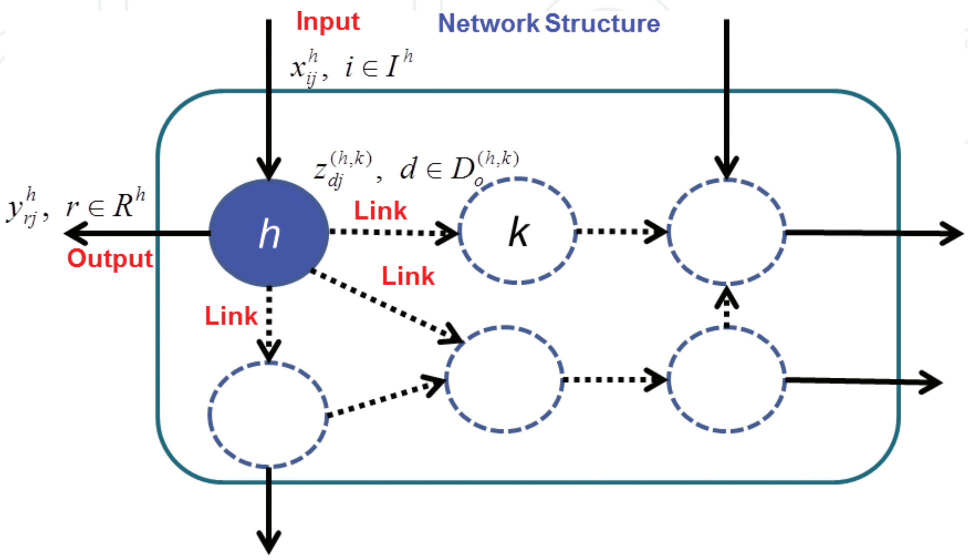

Figure 3. Network structure.

2.5.1. Inputs and outputs

At each sub-process h, there is a set of input measures I^h that flow into the network and a set of output measures R^h that flow out of the network. For DMU_j in set J, let $x_{ij}^h \in \Re_+^{I^h}$ and $y_{rj}^h \in \Re_+^{R^h}$ denote the volumes of the ith input measure and the rth output measure at the sub-process h, respectively. Let s_i^{h-} and s_r^{h+} be the slack of the ith input and the rth output at sub-process h, respectively.

2.5.2. Links

Each sub-process may have links to other sub-processes. Let (h, k) denote the link between sub-processes h and k, $h > k$. Let $D^{(h,k)}$ denote the set of link measures on link (h, k). $z_{dj}^{(h,k)} \in \Re_+^{D^{(h,k)+}} \bigcup \Re_+^{D^{(h,k)-}}$ denotes the volume of the dth link in set $D^{(h,k)}$. Each DMU alternatively acts as the DMU_o that is under evaluation. The volume of link d on link (h, k) could be increased or decreased with a slack to improve the efficiency of DMU_o as well.

3. Illustrative examples

This study adopts a dataset covering 24 non-life insurance companies in Taiwan from Kao and Hwang [10] to illustrate the proposed two-phase procedure. **Table 1** summarizes the performance datasheet of 24 non-life insurance companies in Taiwan.

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Banks	DMU_j	Operation expenses	Insurance expenses	Direct written premiums	Reinsurance premiums	Underwriting profit	Investment profit
		(x_{1j})	(x_{2j})	(z_{1j})	(z_{2j})	(y_{1j})	(y_{2j})
Taiwan Fire	1	1,178,744	673,512	7,451,757	856,735	984,143	681,687
Chung Kuo	2	1,381,822	1,352,755	10,020,274	1,812,894	1,228,502	834,754
Tai Ping	3	1,177,494	592,790	4,776,548	560,244	293,613	658,428
China Mariners	4	601,320	594,259	3,174,851	371,863	248,709	177,331
Fubon	5	6,699,063	3,531,614	37,392,862	1,753,794	7,851,229	3,925,272
Zurich	6	2,627,707	668,363	9,747,908	952,326	1,713,598	415,058
Taian	7	1,942,833	1,443,100	10,685,457	643,412	2,239,593	439,039
Ming Tai	8	3,789,001	1,873,530	17,267,266	1,134,600	3,899,530	622,868
Central	9	1,567,746	950,432	11,473,162	546,337	1,043,778	264,098
The First	10	1,303,249	1,298,470	8,210,389	504,528	1,697,941	554,806
KuoHua	11	1,962,448	672,414	7,222,378	643,178	1,486,014	18,259
Union	12	2,592,790	650,952	9,434,406	1,118,489	1,574,191	909,295
Shingkong	13	2,609,941	1,368,802	13,921,464	811,343	3,609,236	223,047
South China	14	1,396,002	988,888	7,396,396	465,509	1,401,200	332,283
Cathay Century	15	2,184,944	651,063	10,422,297	749,893	3,355,197	555,482
Allianz President	16	1,211,716	415,071	5,606,013	402,881	854,054	197,947
Newa	17	1,453,797	1,085,019	7,695,461	342,489	3,144,484	371,984
AIU	18	757,515	547,997	3,631,484	995,620	692,731	163,927
North America	19	159,422	182,338	1,141,951	483,291	519,121	46,857
Federal	20	145,442	53,518	316,829	131,920	355,624	26,537
Royal & Sunalliance	21	84,171	26,224	225,888	40,542	51,950	6491
Aisa	22	15,993	10,502	52,063	14,574	82,141	4181
AXA	23	54,693	28,408	245,910	49,864	0.10	18,980
Mitsui Sumitomo	24	163,297	235,094	476,419	644,816	142,370	16,976

Table 1. Performance of 24 non-life insurance companies in Taiwan.

The inputs of the system:

Operation expenses (x_1): salaries of the employees and various types of costs incurred in daily operation and.

Insurance expenses (x_2): expenses paid to agencies, brokers, and solicitors and other expenses associated with marketing the service of insurance.

The links of the system:

Direct written premiums (z_1): premiums received from insured clients.

Reinsurance premiums (z_2): premiums received from ceding companies.

The outputs of the system:

Under-writing profit (y_1): profit earned from the insurance business.

Investment profit (y_2): profit earned from the investment portfolio.

3.1. Phase-I

Table 2 summarizes the results of Phase-I and Phase-II. In the Phase-I column, for example, when DMU_1 is being evaluated, DMU_o = DMU_1 and the optimal solution of [M1] is $s_{z1}^{+*} = 0$, $s_{z2}^{+*} = 549,067$, $s_{z1}^{-*} = 877,494$, and $s_{z2}^{-*} = 0$. Therefore, D_o^+ = {2}, D_o^- = {1}, and D_o^{free} = {}. The first row includes 2(549,067) and 1(877,494).

When DMU_4 is being evaluated, DMU_o = DMU_4 and the optimal solution of [M1] is $s_{z1}^{+*} = 0$, $s_{z2}^{+*} = 516,873$, $s_{z1}^{-*} = 0$, and $s_{z2}^{-*} = 0$. Therefore, D_o^+ = {2}, D_o^- = {}, andD_o^{free}={1}. The fourth row includes 2(516,873) and 1(0) in the Phase-I column. The solution of Phase-I indicates that D_o^+ = {2}, D_o^- = {}, and D_o^{free}={1}; the optimal solutions of [M4] are s_{z1}^{free-*} = 3,174,850 and s_{z1}^{free+*} =0. This calculation indicates that the natural link, d = 1, acts as an "as-input" item and may have a better solution. Therefore, 1(3,174,850) is recorded under the D_o^- column of Phase-I. DMU_7 and DMU_{18} have solution processes that are similar to DMU_4.

3.2. Phase-II

Because each link may be "as-input" or "as-output", the two links may have four possible combinations of D_o^+ and D_o^-. **Table 4** shows the four categories A, B, C, and D and their link settings. As indicated in the first column of **Table 3**, 15, 3, 3, and 3 DMUs belong to Categories A, B, C, and D, respectively. For instance, DMU_4 in Category A treats the first links as "as-input" (slack = 1,072,937) and is an undesirable output with respect to Stage-1 and a desirable input with respect to Stage-2. Meanwhile, the second set of links is "as-output" (slack = 135,818) and represents a desirable output with respect to Stage-1 but an undesirable input with respect to Stage-2.

Proceeding to Phase-II, which employs [M5], the optimal solutions for the evaluated DMU are listed in **Table 4**. The second column presents four efficiency scores obtained from (M5), Eqs. [E3], [E4], and [E2], which identify the Stage-1 efficiency (E_o^{1*}), Stage-2 efficiency (E_o^{2*}), and overall efficiency (E_o^*), respectively. The third column presents the reference DMU_j of each evaluated DMU_o. The projection points of DMU_o on the frontier which obtain from E_o^* presents at right sides.

The nine efficient DMUs, 1, 2, 3, 5, 11, 12, 20, 22, and 23, are consistent, with all of their performance scores in Stage-1 and Stage-2 being equal to one. The efficiency scores for the inefficient DMUs for both Stage-1 and Stage-2 are less than 1. For instance, DMU_4 has scores of 0.565 and 0.144 in Stage-1 and Stage-2. An obvious means of improving overall efficiency is to focus on Stage-2.

DMU_o	Phase-I					
	$\rho_o^{(I)*}$	D_o^+	D_o^-	D_o^{free}	$\rho_o^{(II)*}$	D_o^-
1	0.269	2(549,067)	1(877,494)			
2	0.149	2(888,783)	1(36,160)			
3	0.106	1(1,524,659)				
		2(612,849)				
4	0.066	2(516,873)		1(0)	0.183	1(3,174,850)
5	0.414	2(5,425,877)	1(1,093,578)			
6	0.219	2(494,470)	1(4,579,487)			
7	0.182	2(2,347,768)		1(0)	0.338	1(10,685,455)
8	0.199	2(2,888,495)	1(2,895,479)			
9	0.124	2(374,247)	1(8,184,538)			
10	0.192	2(1,429,397)	1(1,301,787)			
11	0.029	1(1,362,146)				
		2(466,500)				
12	0.413	2(8837)	1(78,018)			
13	0.186	1(11,144,019)	2(33,853)			
14	0.169	2(692,753)	1(3,258,713)			
15	0.465	2(689,745)	1(4,484,999)			
16	0.190	2(287,116)	1(3,141,120)			
17	0.300	2(954,161)	1(3,063,410)			
18	0.152		1(74,810)	2(0)	0.186	2(995,620)
19	0.333		1(558,474)			
			2(319,958)			
20	0.454	1(13,617)	2(39,418)			
21	0.154		1(145,060)			
			2(17,915)			
22	0.540	1(38,801)				
		2(4295)				
23	0.000	2(16,295)	1(9566)			
24	0.089	1(265,029)	2(585,641)			

$2^{*}(549{,}067)^{+}$:*, the name of the link; +, the slack of the item.

Table 2. Phase-I solutions.

The virtual weight is expressed as $v_i^* x_{ij} / \sum Virtual \quad Input, w_d^{-*} z_{dj} / \sum Virtual\ Input \quad w_d^{+*} z_{dj} / \sum Virtual\ Output$ and $u_r^* y_{rj} / \sum Virtual\ Output$ where $\sum Virtual\ Input = \sum_{i \in I} v_i x_{ij} + \sum_{d \in D_o^-} w_d^- z_{dj}$ and $\sum Virtual\ Output = \sum_{r \in R} u_r y_{rj} + \sum_{d \in D_o^+} w_d^+ z_{dj}$. These equations represent the percentage of each

Categories	A	B	C	D
D_o^+, D_o^-	$D_o^+ = \{2\}$, $D_o^- = \{1\}$	$D_o^+ = \{1,2\}$, $D_o^- = \{\}$	$D_o^+ = \{\}$, $D_o^- = \{1,2\}$	$D_o^+ = \{1\}$, $D_o^- = \{2\}$

Table 3. Sets D_o^+ and D_o^- of each DMU in Phase-II.

DMU_j	E_o^{1*}	E_o^{2*}	E_o^*	Reference DMU	Projected Points					
					(x_{1j})	(x_{2j})	(z_{1j})	(z_{2j})	(y_{1j})	(y_{2j})
1	1.000	1.000	1.000	1	1,178,744	673,512	7,451,757	856,735	984,143	681,687
2	1.000	1.000	1.000	2	1,381,822	1,352,755	10,020,274	1,812,894	1,228,502	834,754
3	1.000	1.000	1.000	3	1,177,494	592,790	4,776,548	560,244	293,613	658,428
4	0.565	0.144	0.168	22	601,320	386,832	2,101,914	507,681	2,842,519	177,331
5	1.000	1.000	1.000	5	6,699,063	3,531,614	37,392,862	1,753,794	7,851,229	3,925,272
6	0.654	0.316	0.437	12,22	1,384,733	668,363	4,734,713	976,808	4,422,004	415,058
7	0.300	0.212	0.296	22	1,679,395	1,102,796	5,467,038	1,530,389	8,625,473	439,039
8	0.333	0.223	0.316	22	2,382,571	1,564,544	7,756,129	2,171,174	12,237,025	622,868
9	0.322	0.112	0.213	22	1,010,217	663,372	3,288,623	920,585	5,188,537	264,098
10	0.308	0.395	0.423	2,22	1,303,249	1,057,171	6,739,349	1,437,967	4,040,010	554,806
11	1.000	1.000	1.000	11	1,962,448	672,414	7,222,378	643,178	1,486,014	18,259
12	1.000	1.000	1.000	12	2,592,790	650,952	9,434,406	1,118,489	1,574,191	909,295
13	0.976	0.020	0.345	5,22	2,558,630	1,368,802	13,923,383	769,865	3,609,236	1,449,235
14	0.310	0.206	0.284	22	1,396,002	916,702	4,544,491	1,272,140	7,169,973	364,952
15	0.591	0.516	0.702	12,22	1,721,308	651,063	6,056,436	1,001,547	3,489,394	555,482
16	0.460	0.210	0.332	12,22	712,644	415,071	2,369,909	586,830	3,069,552	197,947
17	0.215	0.254	0.343	22	1,422,899	934,363	4,632,050	1,296,650	7,308,093	371,984
18	0.820	0.201	0.240	22	757,515	497,432	2,465,985	690,305	3,890,642	198,035
19	0.582	0.312	0.474	5,22	159,422	102,620	556,110	134,910	755,528	46,857
20	1.000	1.000	1.000	20	145,442	53,518	316,829	131,920	355,624	26,537
21	0.458	0.265	0.286	22	24,829	16,304	80,827	22,626	127,524	6491
22	1.000	1.000	1.000	22	15,993	10,502	52,063	14,574	82,141	4181
23	1.000	1.000	1.000	23	54,693	28,408	245,910	49,864	0	18,980
24	0.504	0.073	0.177	22	163,297	107,231	531,590	148,806	838,704	42,690

Table 4. Final solutions' summary.

input or "as-input" link in the overall virtual input weight and the percentage of each output or "as-output" link in the overall virtual output weight. As shown at **Table 5**, it indicates the improving ratio of each inefficient DMU. For instance, DMU_4 has scores of 0.565 and 0.144 in Stage-1 and

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DMU_j	E_o^*	Input Items		Intermediate Items				Output Items	
		$v_1x_1^*$	$v_2x_2^*$	$w_1z_1^{-*}$	$w_2z_2^{-*}$	$w_1z_1^{+*}$	$w_2z_2^{+*}$	$u_1y_1^*$	$u_2y_2^*$
1	1.000	76%	15%	9%	—	—	10%	7%	83%
2	1.000	84%	8%	8%	—	—	8%	8%	84%
3	1.000	4%	96%	—	—	19%	2%	0%	78%
4	0.168	53%	24%	24%	—	—	8%	8%	85%
5	1.000	78%	14%	8%	—	—	4%	10%	86%
6	0.437	26%	48%	26%	—	—	20%	20%	60%
7	0.296	33%	33%	33%	—	—	0%	28%	72%
8	0.316	33%	33%	33%	—	—	73%	10%	17%
9	0.213	33%	33%	33%	—	—	33%	33%	33%
10	0.423	59%	21%	21%	—	—	2%	2%	97%
11	1.000	1%	99%	—	—	91%	1%	8%	1%
12	1.000	7%	73%	20%	—	—	48%	3%	49%
13	0.345	92%	4%	—	4%	88%	—	8%	4%
14	0.284	33%	33%	33%	—	—	70%	9%	21%
15	0.702	21%	58%	21%	—	—	17%	26%	57%
16	0.332	28%	44%	28%	—	—	20%	20%	61%
17	0.343	33%	33%	33%	—	—	33%	11%	55%
18	0.240	25%	25%	25%	25%	—	—	50%	50%
19	0.474	25%	25%	25%	25%	—	—	44%	56%
20	1.000	2%	96%	—	2%	45%	—	40%	15%
21	0.286	25%	25%	25%	25%	—	—	40%	60%
22	1.000	55%	45%	—	—	23%	23%	32%	23%
23	1.000	4%	96%	—	—	—	100%	0%	0%
24	0.177	33%	33%	—	33%	44%	—	23%	33%

Table 5. Virtual weight percentage.

Stage-2. An obvious means of improving overall efficiency is to focus on Stage-2 output item $u_2y_2^*$; it is 85% of output and as-output items.

4. Discussion and conclusions

The objective of efficiency assessment is to identify weaknesses such that the appropriate steps to improve the entire system's performance. This chapter introduces a two-phase procedure to evaluate the two-stage and network models with "free" links. This new model adopts SBM and considers not only the input and output slacks in the objective function but also the slacks of links. The resultant DEA scores provide completely information on how to project inefficient DMUs onto the DEA frontier for specific two-stage processes. Instead of the two conflicting roles that each link plays in existing models, each link plays a single role in the proposed two-phase process system in that it is either desirable or undesirable. The SBM model in this chapter counts the slacks associated with links in the efficiency scores, overcoming the hurdle. The bank case study takes the example on adjustment in the slacks and defines the best practice performance that the DMU under evaluation will need to attain to achieve the best efficiency. To achieve the best-practice efficiency, each DMU determines a set of weights for input, output, and link, where the links are designated as either "as-input" or "as-output". Input and as-input measures reduce slacks, while output and as-output measures increase slacks to reach their targets on the production frontier. This study only introduces a two-stage procedure to assess the entire system. It also can be extended to more complex network processes, applied in series multistage, share resource (Chen et al. [21] and Liang et al. [22]), dynamic network DEA (Tone & Tsutsui [2] and Kao [13]), assurance region (Thompson et al. [23]), cone ratio model (Charnes et al. [24]), and virtual weight analysis models (Sarrico & Dyson [25]) in future research.

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Malmquist Index with Time Series to Data Envelopment Analysis

Jhon Jairo Vargas Sánchez

Additional information is available at the end of the chapter

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Abstract

This chapter presents a new temporal data envelopment analysis (DEA) model that overcomes some weaknesses of the window analysis and Malmquist index. New model allows to work with time series. For each series the best of a set of ARIMA models is selected, and a forecast for two periods it is possible. Changes in efficiency of different decision making units (DMUs) are analyzed and the use of temporal series makes it easy to include Malmquist forecasts. The implementation of the new model in business administration or supply chain management can be useful because it considers more than two periods in contrast with classical Malmquist method, for that, control of efficiency over time is improved by changing deterministic univariate variables for time series. The last them have the structure of correlation and they get even more real modeling.

Keywords: data envelopment analysis, Malmquist index, DEA change over time, time series, forecast

1. Introduction

Data envelopment analysis (DEA) is a widely used methodology to evaluate the performance of different organizational systems. A good definition of DEA can be found in [1], it is a nonparametric technique used to evaluate the relative efficiencies of a set of DMUs (decision making units). Examples of DMUs can be a factories, countries, sections of factories, universities, supply chains and hospitals. For multiple applications, here are a few of the most notable, performance in healthcare sector [2], assessing the efficiency of wastewater treatment plants [3], environmental policy [4], oil refineries [5], finances institutions [6] and environmental performance [7, 8].

DEA was created by Charnes et al. [9] and the methodology consists in compares DMUs with a frontier of efficiency. The basic DEA model is the CCR (Charnes, Cooper and Rhodes). There are two CCR models, the primal form CCR and dual form CCR.

The dual form CCR is based on optimal weights (u^*, v^*). A linear programming obtain an optimal solution to maximize the ratio $\frac{virtual-output}{virtual-input} = \frac{u_1 y_{1o} + \ldots + u_s y_{so}}{v_1 x_{1o} + \ldots + v_m x_{mo}}$,

where s is the number of outputs, m is the number of inputs and (u, v) are the weights (multipliers) assigned to different input and output, y_{jo} is the jth output of DMU observed $(j = 1, \ldots, s)$, x_{io} is the ith input of DMU observed $(i = 1, \ldots, m)$, more details are given on [10].

The ratio above needs the constraints that the ratio of virtual output vs. virtual input should not exceed 1 for every DMU. So the complete CCR model is

$$\begin{gathered} \theta = \frac{u_1 y_{1o} + \ldots + u_s y_{so}}{v_1 x_{1o} + \ldots + v_m x_{mo}} \\ \max_{u,\, v} \\ Subject\ to \\ \frac{u_1 y_{1o} + \ldots + u_s y_{so}}{v_1 x_{1o} + \ldots + v_m x_{mo}} \leq 1 \\ v_1, v_2, \ldots, v_m \geq 0 \\ u_1, u_2, \ldots, u_m \geq 0 \end{gathered} \tag{1}$$

The primal form of CCR (development form) is based on distances from frontier efficiency. The following model is a primal CCR input oriented in its matrix form:

$$\begin{gathered} \min_{\lambda,\, \theta} \theta \\ \text{Subject to} \\ \theta x_o - X\lambda \geq 0 \\ Y\lambda \geq y_o \\ \lambda \geq 0 \\ \lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)^T, \end{gathered} \tag{2}$$

where n is the number of DMUs, X and Y are the matrixes of input and output respectively, λ is a semipositive vector in R^n. In DEA theory, the construction of primal CCR needs a production possibility set (PPS). The PPS, denoted by P, has 4 properties. The 4th propertie says "*Any semipositive linear combination of activities in P belongs to P*". In this property vector λ appears. But, if an intuitive explanation is wanted, vector λ helps building the frontier of efficiency. Details in [10].

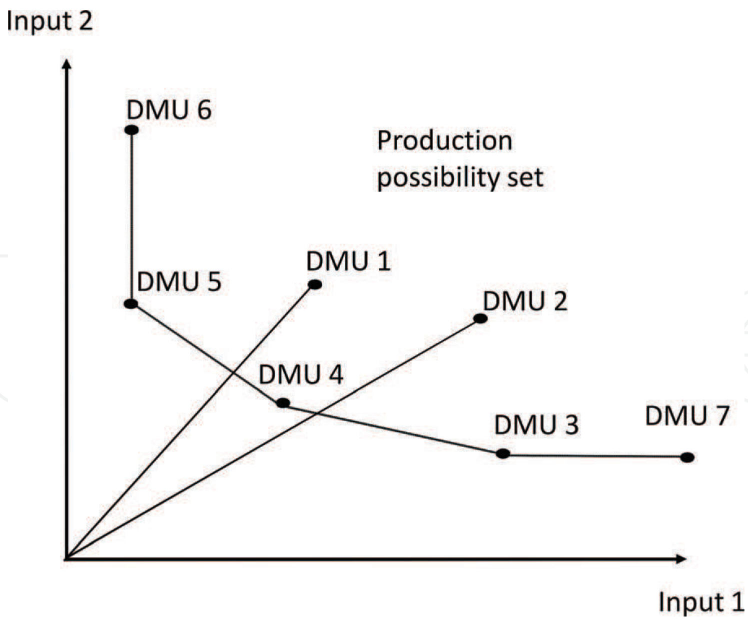

Figure 1. DMUs, frontier efficiency and production possibility set.

In order to have a better understanding, **Figure 1** shows a set of DMUs with 2 inputs and 1 output normalized to 1 (imagine it in the third dimension). Note that, in **Figure 1**, the frontier efficiency is formed by DMUs 3, 4, 5, 6 and 7 through λ_i, in this case, $i = 1, \ldots, 7$. DMUs 1 and 2 are less efficient because they need a contraction to get the frontier. DMU 1 is more efficient than DMU 2, because the distance between DMU 1 and the frontier is shorter than the distance between DMU 2 and frontier. Note the production possibility set and note that the contraction is equivalent to θ in model Eq. (2). Details in [10].

The model Eq. (2) has a variation when it is output oriented. The following model is the CCR output oriented in its matrix form:

$$\begin{gathered} \max_{\eta,\, \mu} \theta \\ \text{Subject to} \\ x_o - X\mu \geq 0 \\ \eta y_o - Y\mu \leq 0 \\ \mu \geq 0 \\ \mu = \left(\mu_1, \mu_2, \ldots, \mu_n\right)^T, \end{gathered} \tag{3}$$

There are many areas of research in DEA, but the most important have been classified in [11]:

- Several model to measure efficiency. This category includes CCR input and output oriented. Several models also includes radial and non-radial models, constant return scale, variable return scale [12] and additive model [13] which combines both, input oriented and output oriented.

- Methods with multiplier restrictions. This category includes absolute multiplier restrictions [14], cone ratio restrictions [15], assurance regions [16, 17].
- Special considerations regarding the status of variables. The variables non-controllable and non-discretionary variables [18] are include here. It also treats ordinal variable data [19–21] and categorical variables [19].
- Data variation. This category is divided in sensitivity analysis [23–26], data uncertainty and probability-based models [27], and time series data. In the last subcategory are the Malmquist index and window analysis.

According to classification above, one of the categories in which efficiency models are classified is the named variation in the data. In this category there are two models, the based in probabilities and data in time series. The last one, also known as efficiency change over time.

In classical DEA literature, the Malmquist index (MI) and window analysis are the unique methods of DEA change over time. There is some evidence that no new temporal DEA methods have appeared, only MI and window analysis [20, 21]. In recent years, temporal Malmquist with multiple periods has studied in [22], Authors calculated MI in years 2000–2009 for environmental assessment in Europe, Asia and America. Nevertheless, in this investigation, there is no MI that gathers the historical performance in a single measure, nor does it consider time series techniques and it does not make combinations of all the possible temporary changes according to the number of periods, that is, years 2000–2001, 2000–2002, 2000-2003, …, 2000–2009, 2001–2002, 2001–2003, …, 2001–2009, …, 2008–2009. That would be an interesting revision and a new vision of a temporal DEA.

This chapter propose a new temporal MI. This chapter is organized as follows. In Section 2 general considerations of MI are presented, the effects in efficiency and definition. Section 3 shows a brief description of window analysis. Section 4 presents the historical and forecast Malmquist that is a new methodology in DEA change over time. This section presents an application and it gives an example. In Section 5 the conclusions.

2. Malmquist index

The first contribution to DEA change over time is the MI, see [23]. The first construction of this index based on DEA methodology is the radial Malmquist [24], however there were efforts to consider non-radial Malmquist based in slacks measures [25, 26]. MI evaluates the productivity change of a DMU between two periods and is an example in comparative statistics analysis [10]. It is defined as the product of "Catch-up" and "Frontier-shift" terms. The catch up (or recovery) is the term that is calculated to study the effect of growth or deterioration in a DMU. The frontier shift (or innovation) term is used to verify the change in the efficient frontiers between the two time periods. In the following subsection these concepts will be explained in more detail.

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2.1. Catch-up and frontier-shift effects

The best and clearest way to describe frontier-shift term is to consider a case with a single input and output, see **Figure 2**. In this one, the points $(x_0, y_0)^1$ and $(x_0, y_0)^2$ symbolize the vector of input and output of the same DMU observed in periods 1 and 2 respectively. The catch-up effect from period 1 to 2 is defined as following expression:

$$Catch - up = \frac{Efficiency\ of\ (x_0, y_0)^2\ with\ respect\ to\ period\ 2\ frontier}{Efficiency\ of\ (x_0, y_0)^1\ with\ respect\ to\ period\ 1\ frontier}$$

The catch-up effect in an input orientation can be expressed by:

$$\text{Catch} - \text{up} = \frac{DE/Dx_0^2}{AC/Ax_0^1}, \tag{4}$$

Where DE symbolizes, in **Figure 2**, the distance between D and E, Dx_0^2 symbolizes the distance between D and abscissa of the point $(x_0, y_0)^2$. Similarly AC is the distance between A and C, A x_0^1 is the distance between A and abscissa of the point $(x_0, y_0)^1$.

The change of $(x_0, y_0)^1$ from frontier of period 1 to frontier of period 2 is called the frontier shift effect at $(x_0, y_0)^1$ and it is evaluate by:

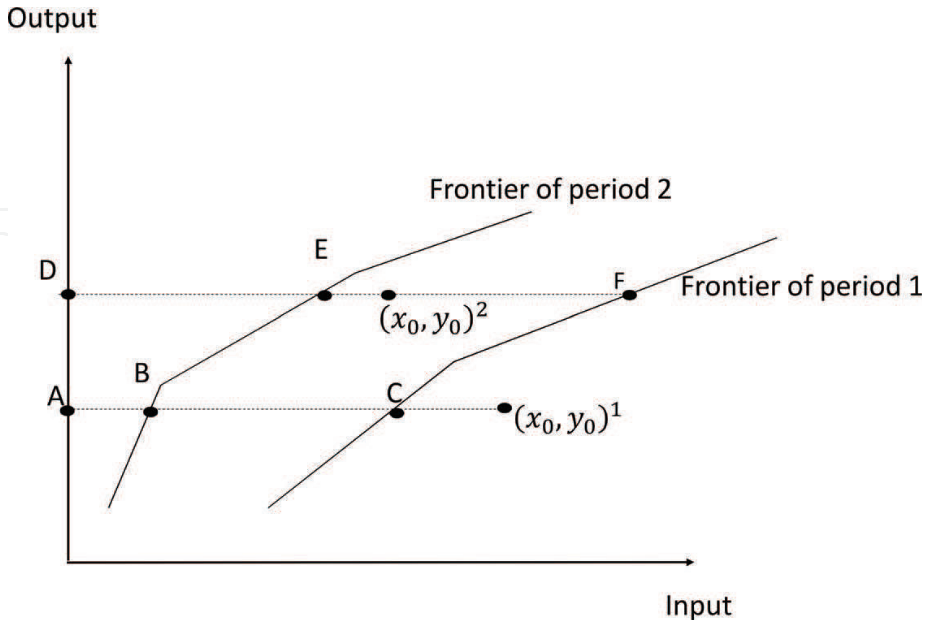

Figure 2. Vectors of inputs and outputs in different periods.

$$\phi_1 = \frac{AC}{AB}. \tag{5}$$

In Eq. (5), if numerator and denominator are divided by the distance between A and abscissa of point $(x_0, y_0)^1$, then:

$$\phi_1 = \frac{\frac{AC}{Ax_0^1}}{\frac{AB}{Ax_0^1}} = \frac{Efficiency\ of\ (x_0, y_0)^1\ with\ respect\ to\ period\ 1\ frontier}{Efficiency\ of\ (x_0, y_0)^1\ with\ respect\ to\ period\ 2\ frontier}. \tag{6}$$

Similarly, the change of $(x_0, y_0)^2$ from frontier of period 1 to frontier of period 2 is called the frontier shift effect at $(x_0, y_0)^2$ and it is evaluate by Eq. (7) or Eq. (8).

$$\phi_2 = \frac{DF}{DE}. \tag{7}$$

$$\phi_2 = \frac{\frac{DF}{Dx_0^2}}{\frac{DE}{Dx_0^2}} = \frac{Efficiency\ of\ (x_0, y_0)^2\ with\ respect\ to\ period\ 1\ frontier}{Efficiency\ of\ (x_0, y_0)^2\ with\ respect\ to\ period\ 2\ frontier}. \tag{8}$$

Using ϕ_1 and ϕ_2, in [10] define the frontier-shift effect by the geometric mean of them, that is:

$$\text{Frontier} - \text{shift} = \phi = \sqrt{\phi_1 \phi_2}. \tag{9}$$

2.2. Definition of MI

The MI is computed as the product of Catch-up and Frontier shift terms, that is:

$$MI = \text{Catch} - \text{up} \times \text{Frontier shift}. \tag{10}$$

According to Eqs. (4)–(10), MI can be calculated by:

$$MI = \frac{Ax_0^1}{Dx_0^2} \sqrt{\frac{DFDE}{ACAB}},$$

where the first term represents the relative change in performance and the second represents the relative change in frontier used to evaluate these performance, see [10].

The Eq. (4) can be expressed by other, using another notation for efficiency score of DMU as follows:

$$Catch - up = \frac{\delta^2\left((x_0, y_0)^2\right)}{\delta^1\left((x_0, y_0)^1\right)}, \tag{11}$$

where $\delta^2\left((x_0, y_0)^2\right)$ denotes the efficiency of DMU observed in period 2 measures by the frontier technology 2 and $\delta^1\left((x_0, y_0)^2\right)$ denotes the efficiency of DMU observed in period 2 measures by the frontier technology 1. In Eq. (11), δ^1 refers frontier efficiency of period 1 and δ^2 refers frontier efficiency of period 2. According to Eqs. (6), (8) and (9), the frontier-shift effect can be expressed by

$$\text{Frontier} - \text{shift} = \left[\frac{\delta^1\left((x_0, y_0)^1\right)}{\delta^2\left((x_0, y_0)^1\right)} \times \frac{\delta^1\left((x_0, y_0)^2\right)}{\delta^2\left((x_0, y_0)^2\right)}\right]^{\frac{1}{2}}. \tag{12}$$

With Eqs. (11) and (12) the following formula is obtained to calculate the MI:

$$MI = \left[\frac{\delta^1\left((x_0, y_0)^2\right)}{\delta^1\left((x_0, y_0)^1\right)} \times \frac{\delta^2\left((x_0, y_0)^2\right)}{\delta^2\left((x_0, y_0)^1\right)}\right]^{1/2}. \tag{13}$$

Using the Eq. (13); the facts that $s = 1, 2$ and $t = 1, 2$; and the notation of a DEA model; the input-oriented radial MI is obtained by the scores of θ given the following 4 linear programs (making s = 1, 2 and t = 1, 2):

$$\begin{gathered} \delta^s\left((x_0, y_0)^t\right) = \min_{\theta,\lambda} \theta \\ \text{subject} \\ \theta x_0^t \geq X^s \lambda \\ y_0^t \leq Y^s \lambda \\ L \leq e\lambda \leq U \\ \lambda \geq 0, \end{gathered} \tag{14}$$

where the vector $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_N)'$; variables λ_i help build the envelopment frontier of efficiency; the vector $e = (1, 1, \ldots, 1)$ size $1 \times N$; X is the input matrix and Y is the output matrix. The matrixes X and Y are arranged such the number of rows are the number of inputs and outputs respectively, and the number of columns are the number of DMUs. For each pair of values (s, t), the model Eq. (14) is calculated N times, where N is the number of DMUs.

In Eq. (14), if $(L, U) = (1, 1)$ then it is a BCC model (Banker Charnes and Cooper), it means that efficiencies are calculated with variable return scale (VRS), see [27], which makes model Eq. (14) suitable to compare DMUs with different sizes. If $(L, U) = (0, \infty)$ then Eq. (14) is a CCR (Charnes, Cooper and Rhodes), it means that efficiencies are calculated with constant return scale (CRS), which makes it suitable to compare DMUs with similar sizes.

The output oriented MI is shown in the following model:

$$\left((x_0, y_0)^t\right) = \min_{\theta, \lambda} \theta \\ \text{subject} \\ x_0^t \geq X^s \lambda \\ \left(\frac{1}{\theta}\right) y_0^t \leq Y^s \lambda \\ L \leq e\lambda \leq U \\ \lambda \geq 0, \tag{15}$$

3. Window analysis

The second contribution of temporal DEA is the window analysis (WA) created by G. Klopp in his doctoral thesis in 1985, see [10]. WA treats each DMU as if it were different in each period of time. Having N time periods, n DMUs and w windows for each DMU, the total of efficiencies to calculate would be $n \times N \times w$, but in WA, a "length of window" p is selected and $n \times p \times w$ efficiencies are calculated instead of total of them. Then, the statistical measures are calculated like mean and variance. In this way, it is possible to verify if a DMU shows stability, deterioration or improvement. In **Table 1**, just to illustrate, there are 2 DMUs of n of them. Each DMU is analyzed in 8 periods, length of window is 5 and there are 4 windows. Note that it is not necessary to evaluate the whole of efficiencies because the window keeps sliding and it is possible to calculate descriptive measures like mean, variance and Range.

According with **Table 1**, it is easy to observe that window analysis does not consider the correlation structure of efficiencies and it does not use statistical technique to estimate efficiencies. Window analysis is a DEA change over time, but there are not time series in input and output variables.

DMU	P1	P2	P3	P4	P5	P6	P7	P8	Mean	Var	Range
1	1.00	0.90	0.93	0.8	0.98						
		0.99	0.90	1.00	1.00	1.00			0.956	0.0032	0.2
			0.85	1.00	1.00	1.00	0.93				
				0.98	0.92	1.00	1.00	0.95			
2	0.78	0.97	0.88	0.92	1.00						
		0.89	0.92	0.98	0.99	0.93			0.941	0.0034	0.22
			1.00	1.00	0.85	0.92	0.93				
				1.00	1.00	1.00	0.92	0.95			
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table 1. Window analysis for two of n DMUs.

4. Historical and forecast Malmquist

Some weaknesses can be highlighted in temporal DEA with its MI and WA techniques. Those techniques are designed for short periods of time, they do not consider random error in the variables and they do not use the dependence structure to estimate the efficiencies. For example, MI works with two periods and forecast is not possible.

There is not a methodology in DEA literature that calculates efficiency taking into account the history of input and output variables, although it could be argued that WA makes it, the history of efficiency is considered in this technique, but not the history of variables neither its correlation structure. There is no MI that gathers, in a single measure, all the possible changes of efficiency period to period.

Given the weaknesses above, a historical and forecast Malmquist is presented. The advantage of this approach is the consideration of stationary and non-stationary time series. These can be large time series and using the possibility to make forecast.

The historical Malmquist is defined in [28] as:

$$Mh = \sqrt[c]{M_{1,2}M_{1,3}\dots M_{1,n}M_{2,3}M_{2,4}\dots M_{2,n}\dots M_{n-2,n-1}M_{n-1,n}}, \quad (16)$$

where $M_{i,j}$ is the classical Malmquist index calculated in periods i and j, $i = 1, 2, \dots, n-1$; $j = 1, 2, \dots, n$; c is the number of combinations of periods given by $\binom{n}{2}$. The principal assumption is that all time series (input and output) have the same number of periods. In the new Mh, the different $M_{i,j}$ are obtained, specifically $\binom{n}{2}$ of them, and each one is calculated by model Eq. (14) or Eq. (15) depending on orientation, but now, $t = 1, 2, \dots, n$ and $s = 1, 2, \dots, n$. To calculate Mh in Eq. (16) the geometric mean is chosen because it is appropriate to average indexes.

4.1. Application in a context

To illustrate the application of historical Malmquist, the five largest industrial centers of Colombia were chosen. They are Antioquia, Atlántico, Bogotá, Cundinamarca (without Bogotá) and Valle. The information was obtained from "Departamento Administrativo Nacional de Estadística de Colombia (DANE)" which translates "National Administrative Department of Statistics of Colombia" from yearly manufacturing survey conducted from 1992 to 2010.

For each industrial center, input and output variables are selected, each of them, with values in time. Each of DMU (Antioquia, Atlántico, Bogotá, Cundinamarca and Valle) has three output variables and five input variables. The following input variables are defined (i) electric energy consumption in Kilowatts-hour, (ii) total assets, (iii) intermediate consumption, (iv) social benefits and (v) salaries. The following output variables are defined (i) permanent remunerated staff

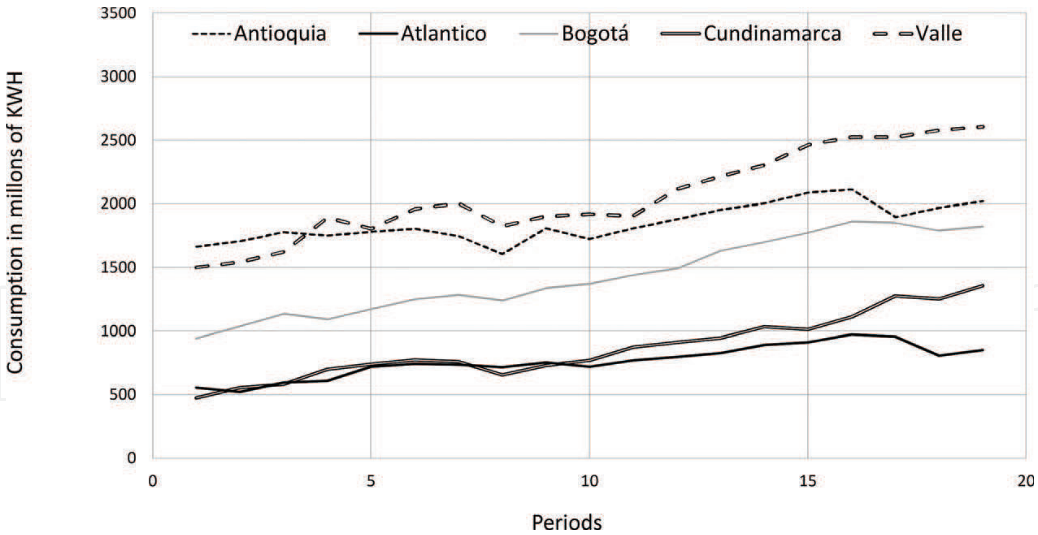

Figure 3. Time series of consumption in KWH of 5 industrial centers.

(PRS), (ii) gross production (GP) and (iii) value added (VA). For details of meaning of variables see [29]. It is important to know that each input or output variable is a time series, then, there are 40 time series (5 DMUs × 8 variables).

The **Figure 3** shows 5 of 40 time series analyzed, these 5 series correspond to consumption of electric energy in millions of Kilowatts-Hour in 5 industrial center (5 DMUs).

4.2. Using time series for application of historical Malmquist

To simplify calculations, all values of variables are divided by 1,000,000, except PRS that was divided by 1000. All the $M_{i,j}$ were calculated suing model Eq. (15) obtaining Mh with $n = 19$ periods. Also Mh is calculated with $n = 21$ periods, in other words including no observed periods 20 and 21, for that, forecasts were established from the following set ARIMA models: ARIMA(1,1,0), ARIMA(2,1,0), ARIMA(1,2,0), ARIMA(2,2,0), ARIMA(0,0,1), ARIMA(0,1,1), ARIMA(0,1,2), ARIMA(0,2,1) and ARIMA(0,2,2).

Each of the 40 time series was modeled through all the above ARIMA and for forecast, in each series, the model with less mean square error (MSE) was chosen.

Table 2 shows the estimations of ARIMA models for time series of Antioquia in PRS variable. This table also shows that ARIMA(0,1,2) model is the best, with less (MSE) and less Bayesian information criterion (BIC). The same procedure for the others two output variables and five input variables was applied, as well as the others industrial centers, for a total of 40 tables like **Table 2**.

Table 3 shows the forecast for Antioquia time series and PRS variable, in addition, it shows the 95% confidence intervals. The same procedure for the others two output variables and five input variables was applied, as well as the others industrial centers, for a total of 40 tables like **Table 3**. Each of these forecasts were used in Eq. (13), model Eqs. (15) and (16), and their results

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	MSE	Coefficients		p value	BIC
ARIMA(1,1,0)	17.928	AR 1	0.651	0.005	3.024
		Constant	−0.293	0.777	
ARIMA(2,1,0)	17.159	AR 1	0.410	0.114	3.071
		AR 2	0.403	0.113	
		Constant	0.045	0.968	
ARIMA(1,2,0)	17.770	AR 1	−0.496	0.041	2.951
		Constant	−0.160	0.878	
ARIMA(2,2,0)	15.778	AR 1	−0.339	0.19	2.918
		AR 2	0.433	0.095	
		Constant	−0.040	0.967	
ARIMA(0,0,1)	134.09	MA 1	−0.947	0.000	5.097
		Constant	98.070	0.000	
ARIMA(0,1,1)	22.830	MA 1	−0.333	0.175	3.266
		Constant	−1.761	0.257	
ARIMA(0,1,2)	11.475	MA 1	−0.800	0	2.669
		MA 2	−0.972	0	
		Constant	−2.177	0.252	
ARIMA(0,2,1)	20.322	MA 1	0.287	0.265	3.085
		Constant	−0.150	0.85	
ARIMA(0,2,2)	18.723	MA 1	0.308	0.247	3.089
		MA 2	−0.337	0.208	
		Constant	−0.170	0.878	

Table 2. ARIMA models for Antioquia time series, variable PRS.

allow to calculate the historical Malmquist with forecast, so, the observed periods and no observed periods (20 and 21) were taken into account.

Table 4 shows the estimations of parameters of ARIMA models selected with less mean square error, they correspond to Antioquia department with three output and five input variables. With models and parameters given in **Table 4**, a forecast is estimated like **Table 3**. The same procedure for the others industrial centers was applied. With these estimations, a good quality forecasts are available for each of temporal input and output variable in each industrial center. Using these forecasts in Eq. (13), model Eqs. (15) and (16), can also be applied to answer the following questions: What can be the historical performances of the DU taking into account the observed and predicted periods?, What the change of efficiency of all DMUs will be in the following two periods, although they do not yet observed? What the instant efficiencies will be in the following two periods, although they do not yet observed? These answers facilitate the

Period	Forecast	Lower limit	Upper limit
20	88.566	81.925	95.206
21	88.123	74.447	101.800

Table 3. Forecast for Antioquia time series, variable PRS.

	Variable	Model	coefficient		p-value	Constant	p-value
Output variable	PRS	ARIMA(0,1,2)	MA 1	−0.800	0.000	−2.177	0.252
			MA 2	−0.972	0.000		
	GP	ARIMA(0,2,1)	MA 1	0.893	0.006	61.650	0.276
	VA	ARIMA(1,2,0)	AR 1	−0.514	0.035	−2.500	0.980
Input variable	Consumption KWH	ARIMA(0,2,1)	MA 1	0. 949	0.004	0.710	0.874
	Total assets	ARIMA(0,1,1)	MA 1	0.892	0.000	857.660	0.000
	Intermediate consumption	ARIMA(0,2,1)	MA 1	0.891	0.005	52.050	0.222
	Social benefits	ARIMA(0,2,1)	MA 1	1.120	0.000	−0.894	0.193
	Salaries	ARIMA(0,2,1)	MA 1	0.9569	0.000	0.812	0.538

Table 4. Estimation of parameters in ARIMA model for Antioquia with 5 variables.

business and operational decision making processes because they would allow flagging of possible problems or failures in output or input levels.

4.3. Using historical Malmquist

Figure 4 shows the levels of Malmquist $M_{i,j}$, with $i = 1, \ldots, 18$ and $j = 1, \ldots, 19$; where $i = 1$ corresponds to year 1992 and $j = 19$ corresponds to year 2010. In total, in this figure there are $c = \binom{19}{2} = 171$ indexes, in other words, the Malmquist calculated with all the possible combinations of periods (1–2, 1–3, …, 1–19, 2–3, …, 2–19, …, 10–11, …, 10–19, …, 18–19). In **Figure 4**, the horizontal axis indicates the position of combinations taken in pairs of periods. The following code helps building this figure.

For *DMU =1 to 5 # for DMUs Antioquia, Atlántico, Bogotá, Cundinamarca and Valle*

    For *i=1 to 18*

        For *j=2 to 19*

            If *(j > i)* ***then***

                Run model Eq. (15) and obtain $\theta = M_{i,j}$

            Else

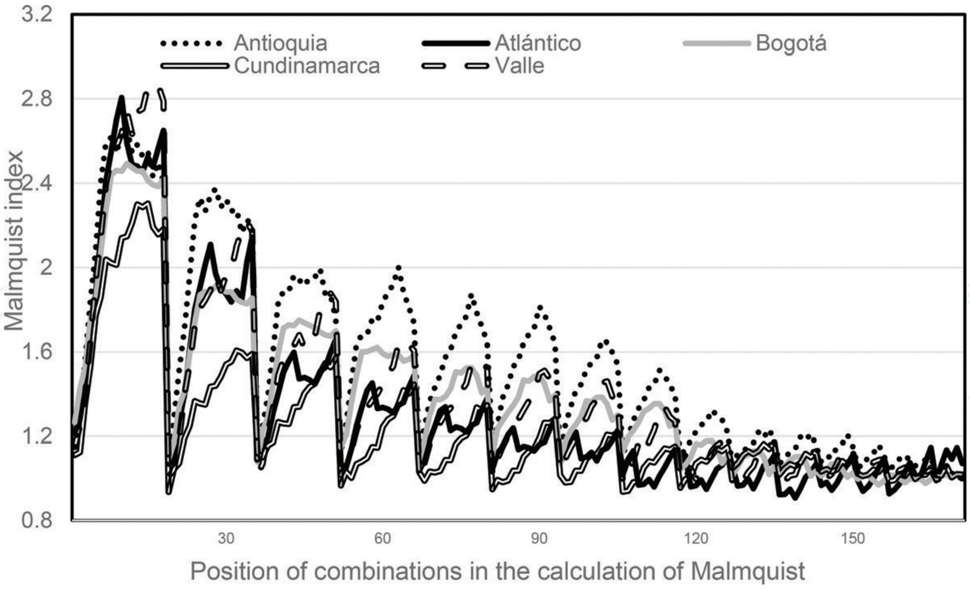

Figure 4. Malmquist indexes for all the combinations of periods.

End

End

End

End

In order to facilitate understanding of **Figure 4**, **Table 5** shows the equivalences between position of combinations and the pairs of periods involved.

Note the importance to consider a historical Malmquist over classical Malmquist. For example, in **Figure 4**, if time period 1–11 is considered (position 10 for this combination in horizontal axis according with **Table 5**) it is clear that Atlántico shows higher change of efficiency ($M_{1,11}$) than Cundinamarca and Antioquia. However, this figure shows that if the Malmquist index were calculated with periods 7–8 (position 94 for this combination in horizontal axis according with **Table 5**) or with periods 2–19 (position 35), Atlántico would begin to show less MI than Antioquia. While position for the combination increases, the MI of Atlántico decreases. For example, note that MI of Antioquia is better than the others with periods 6–19 (position 93) or periods 8–19 (position 116), in fact, after position 40 Antioquia achieves important levels of Malmquist.

The discussion above illustrates the disadvantage of considering MI only with 2 periods when DMUs have historical data and when historical efficiency is required. So, if historical efficiency is needed, MI is too weak, because It treats only two periods and there is not exist a measure that shows the changes of efficiency more than two periods and does not take account all possible changes between periods. For example, MI would be an unfair measure for DMU Antioquia if only periods 1–10 were considered (position 9), when it is evident that in **Figure 4**

Position	**1**	**2**	**…**	**18**	**19**	**20**	**…**	**35**	**36**	**…**	**51**	**52**
Periods involved	1–2	1–3	…	1–19	2–3	2–4	…	2–19	3–4	…	3–19	4–5
Position	…	66	67	…	80	81	…	93	94	…	105	106
Periods involved	…	4–19	5–6	…	5–19	6–7	…	6–19	7–8	…	7–19	8–9
Position	…	116	117	…	126	127	…	135	136	…	143	144
Periods involved	…	8–19	9–10	…	9–19	10–11	…	10–19	11–12	…	11–19	12–13
Position	…	150	151	…	156	157	158	…	161	162	…	165
Periods involved	…	12–19	13–14	…	13–19	14–15	14–16	…	14–19	15–16	…	15–19
Position	166	167	168	169	170	171						
Periods involved	16–17	16–18	16–19	17–18	17–19	18–19						

Table 5. Equivalences between position of combinations and two periods involved.

Antioquia is much stronger than the others. For that, historical Malmquist presented in this chapter possesses more information that explains all the history of DMUs.

4.4. Forecast Malmquist

There are two advantages of historical Malmquist over classical Malmquist. First, historical Malmquist is capable of calculating, in a single measure, the change of efficiency taking into account all the possible combinations of periods. Second, historical Malmquist is capable of calculating forecasts in changes of efficiencies, because it works with time series in its input and output variables.

In **Table 6** the historical Malmquist are calculated with Eq. (16) and they are ranked from high to low. This table also shows the M_h with forecasts in periods 20 and 21.

Table 6 shows temporal efficiencies obtained by forecast, it can be very useful in empresarial organizations. Note that the DMUs Antioquia and Bogotá present the best temporal index. **Table 7** shows what the expected MI can be for the change of periods 20 and 21, although they do not yet observed. Right of table the ranking of forecast Malmquist is presented, so the ranking of DMUs. In this forecast it is notable that Valle could increase in its participation while Bogotá could decrease in its participation. This analysis would be very important for performance in empresarial organizations, because it allows, through the techniques presented, to anticipate the results according the historical trend of data time series in input and output variables of DMUs. The difference between results in **Tables 6** and **7** is that in **Table 6** all possible combinations of periods have been used, while in **Table 7**, only two periods have been used, 20 and 21.

Forecast in Malmquist also helps to establish the instant efficiency, for example, in **Table 8** the efficiencies of periods 20 and 21 can be observed under deterministic output oriented CCR DEA with constant return to scale (CCR-CRS output oriented), see [10]. It can be expected a good participation in ranking of efficiency of Valle in instant periods 20 and 21, although they do not yet observed. So a good recommendation to Valle is that if It wish to obtain the first

DMU	*Mh*	*Mh* with forecast including periods 20 and 21
Antioquia	1.500	1.473
Bogotá	1.360	1.338
Valle	1.340	1.336
Atlántico	1.268	1.270
Cundinamarca	1.203	1.209

Table 6. *Mh* indexes for 5 industrial centers.

DMU	Forecast Malmquist 20–21	DMU ranking	Forecast Malmquist 20–21 ranking
Antioquia	1.007	Antioquia	1.007
Atlántico	1.006	Atlántico	1.006
Bogotá	0.914	Valle	1.005
Cundinamarca	0.997	Cundinamarca	0.997
Valle	1.005	Bogotá	0.914

Table 7. Expected Malmquist according forecast of periods 20 and 21.

DMU	Forecast efficiencies for period 20	Forecast efficiencies for period 21
Antioquia	1	1
Atlántico	1	1
Bogotá	1	1
Cundinamarca	1	1
Valle	1.054	1.052

Table 8. Forecast efficiencies for periods 20 and 21.

position in DEA ranking, It must ensure the increase in the output levels and decrease in the input levels. Because otherwise, plus the fact unexpected increases in the input levels and decrease in the output levels are presented, Valle would have not a good classification in specific periods 20 and 21.

4.5. Analysis of catch-up and frontier effects in historical Malmquist

A great advantage that MI offers is that frontier shift and catch-up effects can be separated. In this analysis these effects have been separated for all the possible combinations of periods. In **Figure 5** the frontier effect is shown and **Figure 6** shows the catch-up effect. Note that frontier effect in **Figure 5** has a great similarity with MI in **Figure 4** with minor differences. The following code helps building the **Figure 5**.

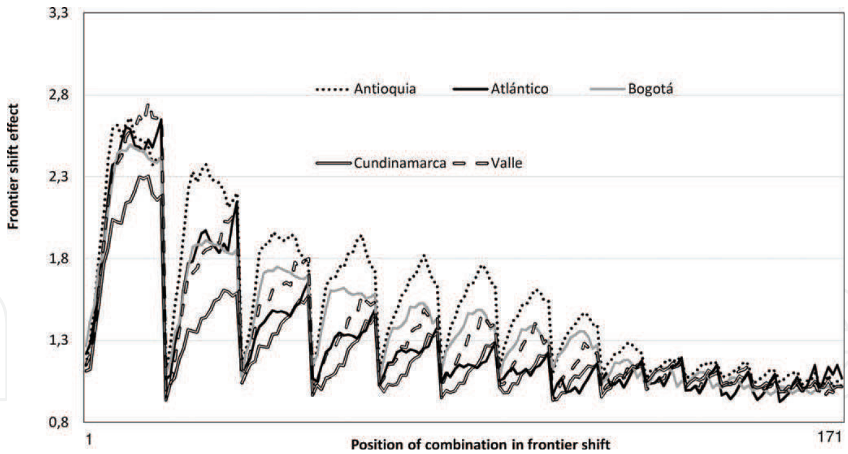

Figure 5. Frontier shift effect after it has been separated from MI.

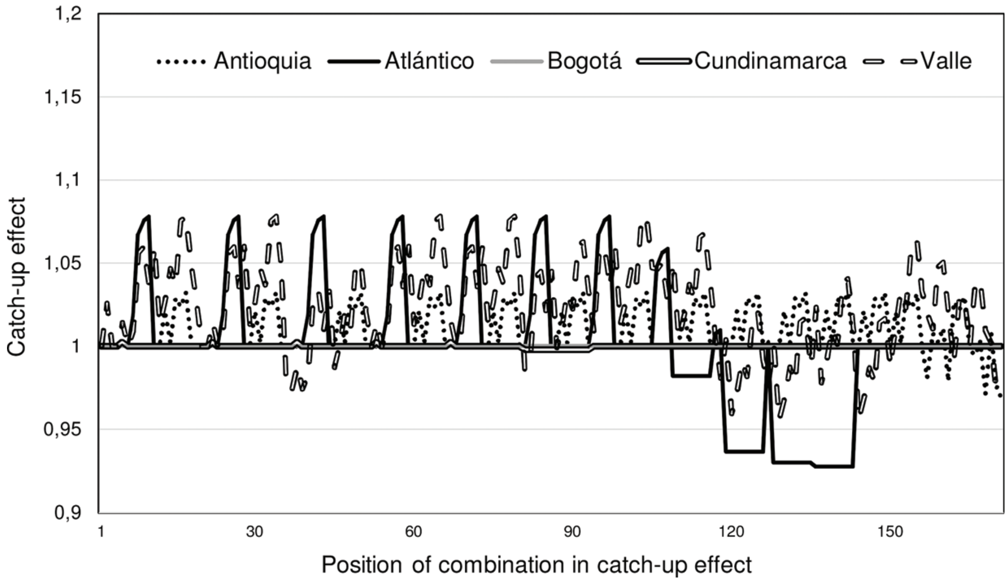

Figure 6. Catch-up effect after it has been separated from MI.

For *DMU =1 to 5 # for DMUs Antioquia, Atlántico, Bogotá, Cundinamarca and Valle*

  For *i=1 to 18*

    For *j=2 to 19*

      If *(j > i)* ***then***

        Run model Eq. (12) and obtain frontier-shift

      Else

    End

End

End

End

The following code helps building the **Figure 6**.

```
For DMU =1 to 5 # for DMUs Antioquia, Atlántico, Bogotá, Cundinamarca and Valle
    For i=1 to 18
        For j=2 to 19
            If (j > i) then
                Run model Eq. (11) and obtain Catch-up effect
            Else
            End
        End
    End
End
```

In Malmquist theory, if catch-up effect 1, it will indicate progress in relative efficiency from period 1 to 2, if catch-up effect 1 and catch-up effect 1 respectively indicate no change and regress in efficiency. If frontier shift effect is bigger than 1, it will indicate progress in the frontier technology around DMU observed from period 1 to 2. Note, in **Figure 6**, that Atlántico and Valle present regress in efficiency after position 110 and 118 respectively, in Atlántico the regress in efficiency is after combinations of periods 8-12, 8–13, …, 12–13. Antioquia also presents regress in efficiency in higher positions.

Applications of historical Malmquist can be presented in industry, economy and supply chain. In general, when there are time series and it is necessary to monitor and to control the changes of efficiency using historical periods.

5. Conclusions

A new model of efficiency change over time has been presented in this chapter based in [28]. That idea arise from explorations of temporal DEA in literature and it was established that there is no new techniques and methodologies, with the exception of Malmquist index and window analysis. The new temporal DEA has been presented like historical Malmquist and its primary advantage is that it accepts time series in input and output variables. Hence, it inherits the advantage of time series technique like use them to make forecast.

A great advantage of new temporal DEA is that it offers an historical information in terms of time, that is a disadvantage of classical Malmquist index that evaluates change of efficiency only in two periods. In this chapter it has been shown that the use of two periods of time to calculate the change of efficiency it is unfair in terms of history of DMUs.

With historical Malmquist it is possible to separate the catch-up and frontier shift effects for all the possible combinations of periods including the next no observed periods, through forecast. This allows to know the trend to progress in relative efficiency, regress in efficiency, progress in the frontier technology and trend to regress in the frontier technology. This will also allow that operational decisions can be taken before efficiency decreases.

Historical Malmquist allows to work both stochastic input and stochastic output variables, because it accepts time series in both cases, in contrast with classical MI that allows deterministic values and it is not common that a DEA model allows to work with probability functions in both input and output.

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An Intuitionistic Fuzzy Group Decision-Making to Measure the Performance of Green Supply Chain Management with TOPSIS Method

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Additional information is available at the end of the chapter

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Abstract

Green supply chain management (GSCM) integrates environmental regulations into supply chain management to diminish the negative effects of supply chain processes on the environment. The environmental problems appeared by an enterprise arise from designing the product and last until the recycling process. GSCM activities include five drivers such as green design, green purchasing, green transformation, green logistics and reverse logistics. In this chapter, the main aim is to explain these drivers and to show how to measure the GSCM success of companies, which operate as tire manufacturers by using an evaluation of a group of experts in their field. The proposed method, intuitionistic fuzzy technique for order preference by similarity to an ideal solution as an effective group decision-making method, helped to identify the alternative company 1 with the best GSCM performance among six different alternative tire companies under the consideration of five important GSCM drivers. The ranking result was as follows: A1 > A3 > A4 > A2 > A6 > A5.

Keywords: intuitionistic fuzzy TOPSIS, group decision-making, green supply chain management

1. Introduction

After the Industrial Revolution, rapid developments in technology and industrialization cause environmental problems to meet the increasing needs. At this point, many countries have begun to implement environment protection rules, which are part of environmental management systems (EMS). Managing and improving environmental performances, increasing resource efficiency, complying with environmental laws and regulations and adapting to changing requirements are part of EMS and helped organizations for maintaining environmental policy. Environmental regulations can differ from country to country. So, these differences create barriers to trade. Firms have initiated various ventures in order to remove trading barriers and be able to make cleaner production and to use natural resources most efficiently as a result of compulsory pressures created by regulatory regimes. One of these powerful ventures is building an integration environmental thinking into supply chain management, which is called green supply chain management (GSCM). Jolley's research [1] supports that EMS and green supply chain practices are complementary to each other. Over the last years, GSCM has an important role to build powerful economic environmental performances at different levels in organizations [2]. To improve green skills, all firms need successful implementation of GSCM within the organization.

In the literature, there are many different definitions for GSCM. However, in general, GSCM means the explicit consideration of ecological dimensions in the planning, operations and management of supply chains [3]. Minimizing or eradicating wastes including hazardous chemical, emissions, energy and solid waste along supply chain process such as product design, material sourcing and selection, manufacturing process, delivery of final product to the consumers and end-of-life management of the product are the main aims of GSCM [4, 5]. In order to reach these main aims and increase the efficiency of green supply chain management, firms apply multi-criteria decision-making techniques. In a highly competitive fuzzy environment, using fuzzy group decision-making methods is more effective to find the optimal solutions.

Therefore, in this chapter, an extended technique for order preference by similarity to an ideal solution (TOPSIS) for group decision-making with intuitionistic fuzzy numbers is proposed to assess GSCM performance of tire manufacturing companies. First of all, performance drivers of GSCM performance are determined with the help of literature review and opinions of academic and industrial experts. After deciding the main drivers of GSCM performances, three decision-makers who have certain experience and expertise give individual opinions about drivers and alternatives. In other studies in this area, the weights of each decision-maker in a specific group are generally ignored; however, in this study, relative importance of each decision-maker's opinions is determined by using intuitionistic fuzzy numbers. Intuitionistic fuzzy weighted averaging (IFWA) operator, developed by Xu in 2007 [6], is utilized to aggregate individual opinions of decision-makers for rating the importance of criteria and alternatives.

This chapter proposes an intuitionistic fuzzy multi-criteria group decision-making with the TOPSIS method for GSCM performance evaluation. In Section 2, many definitions of GSCM are given and researches about GSCM have been explained. The rest of this chapter is organized as follows. In Section 3, the proposed methodology in this chapter is explained. A brief description of intuitionistic fuzzy sets is also given in subSection 1 of Section 3. SubSection 2 of Section 3 presents a detailed description of intuitionistic fuzzy TOPSIS method. In Section 4, a numerical example, which is about GSCM performances of tire manufacturing companies, is demonstrated. Finally, the conclusion of this chapter and obtained results are presented in Section 5.

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2. Green supply chain management

Environmentally responsible manufacturing created a relation between environmental researches in logistics and the reverse logistics. Therefore, the idea of GSCM emerged in this way, and it is said that its history was based on the researches on reverse logistics in 1990s [7]. According to [8], if a definition is to be made about supply chain and green supply chain, this definition depends on the economic, social, environmental, coordination, relationship, efficiency and performance criteria, which belong to business sustainability and supply chain management characteristics.

The GSCM notion in the literature has been defined in many researches and studies in recent years. Some of these definitions have been general and comprehensively covered the whole area, while others have focused on specific aspects [9]. Gilbert [10] explains that GSCM is an integration of traditional supply chain management facilities and environmental criteria. Hervani et al. [11] defined that GSCM is the collection of green purchasing, green manufacturing management, green distribution and reverse logistics. GSCM begins at the point of product design and continues until the end of the product's lifecycle in every step of the supply chain process, including recycling or environmentally friendly eradication of the product [12].

A number of researchers have focused on supply chain management and also GSCM as the potential multi-criteria decision-making problem in recent years. For example, Muduli and Barve [13] have made an attempt to identify main success criteria such as top management commitment, gap analysis, implementation and continual improvement for GSCM implementation in Indian mining industries and used the Analytic Hierarchy Process (AHP) to represent the existing interrelationship between factors in a structured way. Kamolkittiwong and Phruksaphanrat [14] also have tried to implement GSCM strategy of the electronic industry in Thailand to help the new companies that want to enter the market in their study. It aimed to determine the importance level of external and internal critical factors of GSCM strategy implementation. In another research, Toke et al. [15] have found the weights of critical success factors of GSCM in Indian manufacturing industry with the help of AHP steps. Mathiyazhagan et al. [16] examined the pressures for GSCM adoption via AHP. References [17–26] have built AHP and fuzzy AHP models for the evaluation of different GSCM practices. As seen, despite the fact that studies which applied on AHP models are mostly in the majority, in the green supply chain literature, GSCM practices can be often investigated differently by many different multi-criteria decision-making techniques such as TOPSIS, VIKOR, DEMATEL among researchers. For instance, Muralidhar et al. [27] have applied TOPSIS and fuzzy AHP together to evaluate various green supply chain management strategies, which are composed of green procurement, manufacturing, green service to customers and environmental management process. Akman and Piskin [28] have integrated Analytical Network Process (ANP) and TOPSIS to assess GSCM practices performance of 18 green suppliers by utilizing main criteria such as pollution control, environment management system, green products, environmental collaboration and environmental competency. The models [29–33] used in their articles are given as some examples of TOPSIS and fuzzy TOPSIS.

Rostamzadeh et al. [34] concentrated on fuzzy VIKOR to maintain GSCM activities in four laptop manufacturing companies. Main criteria such as green design, green purchasing, green production, green warehousing, green transportation and green recycling were evaluated to rank these companies in this research. According to Malviya and Kant [35], measuring the success of GSCM implementation via a hybrid model which constructed DEMATEL and fuzzy sets was contributed to green supply chain literature. Strategic, organizational, social-cultural, buyer and supplier activity, legislation and technical GSCM practices were the evaluated main factors to compare success and failure assessments in this research. Comparing to other multi-criteria decision-making techniques, in the literature, there are a few studies about GSCM performances under intuitionistic fuzzy environment. However, there is a growing interest about this specific subject. Govindan et al. [36] proposed an intuitionistic fuzzy DEMATEL method to obtain green practices in an efficient manner for the automotive sector. GSCM performances criteria such as reverse logistics, green design, green purchasing, carbon management, supplier environmental collaboration, customer environmental collaboration, ISO 14001 certification, internal management support, environmental performance and economic performance and their interdependencies were improved by applying the DEMATEL technique. It has been determined that automotive firms need to properly implement GSCM in order to avoid the adverse effects of strict regulations and increasing community concerns.

Wan and Li [37] developed a new fuzzy mathematical programming method for solving complex multi-attribute decision-making problems with interval-valued intuitionistic fuzzy sets to determine the weights and make green supplier selection. Green supplier selection is the one of the critical problems of GSCM. According to this research, the focuses of green supplier selection are different from the traditional supplier selections. Li and Wu [38] have improved intuitionistic fuzzy TOPSIS model for green supplier selection, and their findings show that the model can solve this selection problem under uncertain environment effectively.

The performance measurement perspective of GSCM has been supported by various authors. Hervani et al. [39] firstly aimed at determining the GSCM performance tools. After that, with an integrated study, green purchasing, green manufacturing, green marketing and reverse logistics were used in the main definition of GSCM performance. To provide long-term business life in green-based organizations, firms have to focus on all important criteria of GSCM performance. The purposes of this focus on GSCM performance have been identified as making robust external reporting, managing firms in the best way and also making an internal analysis about business and environment. Rao and Holt [2] analyzed supply chain management from the greening perspective and found a link between GSCM practices and necessity of competitive activities. According to them, if GSCM was applied by all organizations, economic performances and competitiveness could be obtainable. Zhu et al. [40] studied on GSCM practices of four different Chinese industries, and they reached the conclusion that the industrial differences affected the adoption of GSCM. Jakhar [41] determined main criteria and subcriteria of GSCM performances. Green supplier partnership performance, green production performance, green delivery and logistics performance are used as main criteria, while cost of raw material, carbon footprint, defect rate, flexibility rate, recycling rate, ordering cost, unit manufacturing cost, capacity utilization level, usage of energy, product quality, production flexibility, transportation cost, greenhouse gas emission, delivery time and delivery reliability are subcriteria. Uygun and Dede [26] applied DEMATEL, ANP and TOPSIS methods under fuzzy environment to make a general evaluation about GSCM main criteria and subcriteria. Green design, green purchasing, green transformation, green logistics and reverse logistics are defined as main criteria, along with product features, material selection, energy usage, life-cycle design, eco-design, design for environment, reusable materials, green manufacturing, green packaging, green stock politics, quality of service, quality of technology, quality regulations, and so on. The main aim of this research is to show the effectiveness of green activities of firms. Surmacz [42] explained why the firms need GSCM performance measurement systems. Recognition of green goals of firms and early warning for failures must be included while considering effective factors of GSCM performance measurement.

As seen, GSCM performance measurement is a very difficult problem for companies. This is mainly the case because measuring environmental performances is indeed a difficult task due to the reasons such as the lack of data, weak technology, cultural and organizational conflicts in an uncertain future. However, in a general view, in this chapter, the components of GSCM performance measurement are determined and used for GSCM evaluation in tire manufacturing companies. These components, which are called Green Design, Green Purchasing, Green Transformation, Green Logistics and Reverse Logistics, are used as criteria of GSCM performance. Green design is an environmental matter that both manufacturers and producers focus on. From the perspective of GSCM, green design proves helpful during the design phase particularly in terms of identifying product features, material selection, energy usage, and so on. Green purchasing is defined as an environmentally sensitive purchasing practice. According to Min and Galle [43], it is an ongoing procedure of recycling reusable or recyclable materials. It helps to satisfy customers and to ensure the brand image of the companies. Green transformation comprises all transformation activities such as green manufacturing, green packaging and green stock policies for production process of a product [44]. Green logistics uses an environmental way to deliver products and services. It aims to preserve resources to satisfy requirements about ecological balance [45]. Reducing idle use will help improve work efficiency. Reverse logistics is briefly about reusing the product materials. It manages networks which help product returns, remanufacturing, recovery, reuse and redistribution [46].

3. Methodology

A number of researchers have focused on supply chain management and also on green supply chain management as the potential multi-criteria decision-making problems in recent years. The evidence from the literature, therefore, is that there is a lack of consensus on the impact of GSCM on performance outcomes. This conflict was recognized and discussed in different studies including those by Eltayeb et al. and Zhu et al. [47, 48]. Zhu et al. [48] argued that the conflicting findings have the potential to become a barrier for organizations that intend to implement GSCM. In this chapter, the proposed performance evaluation model for GSCM is a hybrid model which combines TOPSIS and intuitionistic fuzzy set.

3.1. Intuitionistic fuzzy set

The first appearance of the concept of fuzzy logic came in 1965 when Zadeh published a paper entitled "Fuzzy Sets" in a journal named Information and Control [49]. Fuzzy logic, also expressed as the adaptation of mathematics to the real world, is based on uncertainties.

The fuzzy set theory, unlike the classical known set theory, operates according to the Aristo logic and allows the partial membership of an element to a set. For example, this suggests adding less sharp values into the cluster such as very long-long-medium-short-very short, hot-warm-less cold-cold-very cold values instead of using sharp values such as long-short, hot-cold, fast-slow, black and white. These intermediate values are in the form of verbal expressions and are called fuzzy variables. The intuitive fuzzy set was developed for the first time by Atanassov [50] and has appeared in the literature as a generalized version of the fuzzy set. According to Atanassov's definition [50], intuitionistic fuzzy set A in a nonempty set X can be shown as:

A $= \{\langle x, \mu_A(x), v_A(x)\rangle | x \in X\}$ where $\mu_A(x) :\to [0,1]$, $v_A(x) : X \to [0,1]$ are membership functions and nonmembership functions separately.

$$0 \le \mu_A(x) + v_A(x) \le 1 \tag{1}$$

$\pi_A(x)$ is a third parameter of intuitionistic fuzzy set. $\pi_A = 1 - \mu_A(x) - v_A(x)$ is known as the degree of indeterminacy of x which belongs to A or not. So, it is clear that $0 \le \pi_A(x) \le 1, \forall x \in X$. On the other hand, if the $\pi_A(x)$ is small, an understanding about x is more certain. If the $\pi_A(x)$ is big, an understanding about x is more uncertain. Apparently, when $\mu_A(x) = 1 - v_A(x)$ for all elements of the universe, the ordinary fuzzy set construction is retrieved [51]. A and B are intuitionistic fuzzy sets of the set X, and multiplication operator is exhibited as in Atanassov's research [50].

$$\mathrm{A} \otimes \mathrm{B} = \{\mu_A(x).\mu_B(x), v_A(x) + v_B(x) - v_A(x).v_B(x) x \in X|\} \tag{2}$$

3.2. Intuitionistic fuzzy TOPSIS

Technique for order preference by similarity to ideal solution methods (TOPSIS), one of the multi-criteria decision-making techniques, was developed by Hwang and Yoon in 1981 [52]; it is based on the shortest distance to positive ideal solution and the farthest distance to negative ideal solution and aims to rank alternatives according to distance measurement. TOPSIS also differs from other multi-criteria decision-making techniques in terms of being a technique that solves all the evaluation criteria at the same time and presents a single distribution to the decision-makers. Furthermore, its literature history is really powerful. In this chapter, the TOPSIS method intends to achieve the ultimate decision by expanding intuitively fuzzy environment.

Let $A = \{A_1, A_2, ..., A_m\}$ be a set of alternatives, while $C = \{C_1, C_2, ..., C_n\}$ be a set of criteria. The relative importance of decision-makers in group of l decision-makers is also a part of the account. The fact that some of decision-makers have different knowledge, experiences and education level differentiates the importance levels of their opinions.

$\lambda = \{\lambda_1, \lambda_2, ... \lambda_l\}$ is the weighted vector of decision-makers $\lambda_k \geq 0 \;\; k = 1, 2, ...l$ and $\sum_{k=1}^{l} \lambda_k = 1$.

$R^{(k)} = (r_{ij}^{(k)})_{mxn}$: kth decision-maker's intuitionistic fuzzy decision matrix.

$r_{ij}^{(k)} = (\mu_{ij}^{(k)}, v_{ij}^{(k)}, \pi_{ij}^{(k)})$: ith alternatives of an intuitive value from jth criterion given by kth decision-maker.

$\mu_{ij}^{(k)}$: jth criterion membership degree of ith alternatives to kth decision-maker.

$v_{ij}^{(k)}$: jth criterion nonmembership degree of ith alternatives to kth decision-maker.

$\pi_{ij}^{(k)}$: the uncertainty degree to kth decision-maker.

According to all given definitions, the hybrid use of the intuitive fuzzy set theory with TOPSIS is proposed by Boran et al. [53], and the steps of the Intuitionistic Fuzzy TOPSIS method are as follows:

Step 1: Determination of the weights of decision-makers.

Since group decision-making is a matter of concern, the significance ratings within the group of expert decision-makers are expressed in linguistic terms based on the fuzzy set theory, and at later stages, these terms are transformed into intuitive fuzzy numbers.

$D_k = (\mu_k, v_k, \pi_k)$ is an intuitionistic fuzzy number for rating kth decision-maker.

The weight of kth decision maker can be calculated, as shown in Eq. 3:

$$\lambda_k = \frac{(\mu_k + \pi_k(\frac{\mu_k}{\mu_k + v_k}))}{\sum_{k=1}^{l}(\mu_k + \pi_k(\frac{\mu_k}{\mu_k + \upsilon_k}))} \tag{3}$$

and also $\lambda_k \geq 0 \; k = 1, 2, ...l$ ve $\sum_{k=1}^{l} \lambda_k = 1$.

Step 2: Conversion of decision-makers' evaluation about alternatives into aggregated intuitionistic fuzzy decision matrix.

The intuitive fuzzy weighted averaging (IFWA) operator proposed by Xu [6] is used because all the decision-makers' evaluations on the subject can be presented as a group decision and no loss of thought by any party in the group occurs.

According to this operator, different evaluations can be presented as a single evaluation.

$$\begin{aligned} r_{ij} &= IFWA_\lambda(r_{ij}^{(1)}, r_{ij}^{(2)}, ..., r_{ij}^{(l)}) = r_{ij}^{(1)}\lambda_1 \oplus r_{ij}^{(2)}\lambda_2 \oplus ... \oplus r_{ij}^{(l)}\lambda_l \\ &= \left[1 - \prod_{k=1}^{l}(1 - \mu_{ij}^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(\upsilon_{ij}^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(1 - \mu_{ij}^{(k)})^{\lambda_k} - \prod_{k=1}^{l}(\upsilon_j^{(k)})^{\lambda_k}\right] \end{aligned} \tag{4}$$

In Eq. 4, the given $r_{ij} = (\mu_{ij}, v_{ij}, \pi_{ij})$ $(i = 1, 2..., m; \mathrm{j} = 1, 2, ...\mathrm{n})$ is an element of R aggregated intuitionistic fuzzy decision matrix. R matrix can be shown as follows:

$$R = \begin{bmatrix} (\mu_{11}, v_{11}, \pi_{11}) & (\mu_{12}, v_{12}, \pi_{12}) & \cdots & (\mu_{1n}, v_{1n}, \pi_{1n}) \\ (\mu_{21}, v_{21}, \pi_{21}) & (\mu_{22}, v_{22}, \pi_{22}) & \cdots & (\mu_{2n}, v_{2n}, \pi_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (\mu_{m1}, v_{m1}, \pi_{m1}) & (\mu_{m2}, v_{m2}, \pi_{m2}) & \cdots & (\mu_{mn}, v_{mn}, \pi_{mn}) \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

Step 3: Calculation of the weights of criteria.

As each decision-maker may hold a different opinion on the criterion, the criterion taken for the evaluation in different topics may also be different from each other. In order to reflect this situation to the calculations, each decision-maker's thoughts about the criteria must be expressed in intuitive fuzzy values and combined with the idea of group decision without loss of thought. For this reason, a different IFWA operator, proposed by Xu [6] for the weights of the following criteria, is used as follows:

$$\begin{aligned} w_{ij} &= IFWA_{\lambda}(w_j^{(1)}, w_j^{(2)}, \ldots, w_j^{(l)}) = \lambda_1 w_j^{(1)} \oplus \lambda_2 w_j^{(2)} \oplus \ldots \oplus \lambda_l w_j^{(l)} \\ &= \left[1 - \prod_{k=1}^{l}(1-\mu_j^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(\upsilon_j^{(k)})^{\lambda_k}, \prod_{k=1}^{l}(1-\mu_{ij}^{(k)})^{\lambda_k} - \prod_{k=1}^{l}(\upsilon_j^{(k)})^{\lambda_k}\right] \end{aligned} \tag{5}$$

$W = \{w_1, w_2, w_3, \ldots. \text{w}_j\}$ are the weights calculated for criteria. Each weight is expressed like that: $W_j = (\mu_j, v_j, \pi_j)$ $(j = 1, 2, \ldots, \text{n})$.

Step 4: Construction of aggregated weighted intuitionistic fuzzy decision matrix.

The aggregated weighted intuitionistic fuzzy decision matrix is constructed by combining with criteria weights and the aggregated intuitionistic fuzzy decision matrix, which is determined in second step. The following definition is [50]:

$$R' = R \otimes W = (\mu_{ij}', v_{ij}') = \left\{\left\langle x, \mu_{ij}.\mu_j, v_{ij} + v_j - v_{ij}.v_j \right\rangle | x \in X\right\} \tag{6}$$

and

$$\pi'_{ij} = 1 - v_{ij} - v_j - \mu_{ij}.\mu_j + v_{ij}.v_j \tag{7}$$

$r'_{ij} = (\mu'_{ij}, v'_{ij}, \pi'_{ij})$ $(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$ are the elements of matrix.

The aggregated weighted intuitionistic fuzzy decision matrix (R') can be shown as follows:

$$R' = \begin{bmatrix} (\mu'_{11}, v'_{11}, \pi'_{11}) & (\mu'_{12}, v'_{12}, \pi'_{12}) & \cdots & (\mu'_{1n}, v'_{1n}, \pi'_{1n}) \\ (\mu'_{21}, v'_{21}, \pi'_{21}) & (\mu'_{22}, v'_{22}, \pi'_{22}) & \cdots & (\mu'_{2n}, v'_{2n}, \pi'_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (\mu'_{m1}, v'_{m1}, \pi'_{m1}) & (\mu'_{m2}, v'_{m2}, \pi'_{m2}) & \cdots & (\mu'_{mn}, v'_{mn}, \pi'_{mn}) \end{bmatrix} = \begin{bmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & r'_{22} & \cdots & r'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r'_{m1} & r'_{m2} & \cdots & r'_{mn} \end{bmatrix}$$

Step 5: Calculation of intuitionistic fuzzy positive-ideal solution and intuitionistic fuzzy negative-ideal solution.

J_1 is defined as the set of benefit criteria, and J_2 is also defined as the set of cost criteria. At this point, A^* is intuitionistic fuzzy positive-ideal solution and A^- is intuitionistic fuzzy negative-ideal solution. Respectively, solutions are formulated as:

$$A^{*} = (r_1^{'*}, r_2^{'*}, \ldots, r_n^{'*}),\ r_j^{'*} = (\mu_j^{'*}, v_j^{'*}, \pi_j^{'*})\ j = 1, 2, \ldots, n$$
$$A^{-} = (r_1^{'-}, r_2^{'-}, \ldots, r_n^{'-}),\ r_j^{'-} = (\mu_j^{'-}, v_j^{'-}, \pi_j^{'-})\ j = 1, 2, \ldots, n \tag{8}$$

$$\mu_j^{'*} = \left\{ \left(\max_i \{\mu_{ij}^{'}\} \mid j \in J_1 \right), \left(\min_i \{\mu_{ij}^{'}\} \mid j \in J_2 \right) \right\} \tag{9}$$

$$v_j^{'*} = \left\{ \left(\min_i \{v_{ij}^{'}\} \mid j \in J_1 \right), \left(\max_i \{v_{ij}^{'}\} \mid j \in J_2 \right) \right\} \tag{10}$$

$$\pi_j^{'*} = \left\{ \left(1 - \max_i \{\mu_{ij}^{'}\} - \min_i \{v_{ij}^{'}\} \mid j \in J_1 \right), \left(1 - \min_i \{\mu_{ij}^{'}\} - \max_i \{v_{ij}^{'}\} \mid j \in J_2 \right) \right\} \tag{11}$$

$$\mu_j^{'-} = \left\{ \left(\min_i \{\mu_{ij}^{'}\} \mid j \in J_1 \right), \left(\max_i \{\mu_{ij}^{'}\} \mid j \in J_2 \right) \right\} \tag{12}$$

$$v_j^{'-} = \left\{ \left(\max_i \{v_{ij}^{'}\} \mid j \in J_1 \right), \left(\min_i \{v_{ij}^{'}\} \mid j \in J_2 \right) \right\} \tag{13}$$

$$\pi_j^{'-} = \left\{ \left(1 - \min_i \{\mu_{ij}^{'}\} - \max_i \{v_{ij}^{'}\} \mid j \in J_1 \right), \left(1 - \max_i \{\mu_{ij}^{'}\} - \min_i \{v_{ij}^{'}\} \mid j \in J_2 \right) \right\} \tag{14}$$

Step 6: Calculation of positive and negative separation measures.

To measure the separation between alternatives on the positive intuitive fuzzy ideal solution and the negative intuitive fuzzy ideal solution, calculation of distance measurement can vary. For instance, the TOPSIS method generally applies to Euclidean distance measurement; however, in the literature, to remove some mathematical set obstacles, Hamming distance measurement and normalized distance measurement are proposed by Szmidt ve Kacprzyk in 2000 [54]. In this chapter, Hamming distance measurement is used to measure the separation between the positive and the negative measurement of intuitive fuzzy ideal solution.

According to this, the following formulas are used to calculate for S_i^* and S_i^-:

$$S_i^{*} = \frac{1}{2} \sum_{j=1}^{n} \left[\left| \mu_{ij}^{'} - \mu_j^{'*} \right| + \left| v_{ij} - v_j^{'*} \right| + \left| \pi_{ij}^{'} - \pi_{ij}^{'*} \right| \right], i = 1, 2, \ldots, m \tag{15}$$

$$S_i^{-} = \frac{1}{2} \sum_{j=1}^{n} \left[\left| \mu_{ij}^{'} - \mu_j^{'-} \right| + \left| v_{ij}^{'} - v_j^{'-} \right| + \left| \pi_{ij}^{'} - \pi_{ij}^{'-} \right| \right], i = 1, 2, \ldots, m \tag{16}$$

Step 7: Calculation of the relative closeness coefficient to the intuitionistic ideal solution.

The relative closeness coefficient of an alternative with respect to the intuitionistic fuzzy positive ideal solution is calculated as follows:

$$C_i^{*} = \frac{S_i^{-}}{S_i^{*} + S_i^{-}},\ \ 0 \le C_i \le 1\ ,\ \ i = 1, 2, \ldots, m \tag{17}$$

Step 8: Ranking the alternatives.

Alternatives are ranked according to descending order of relative closeness coefficient value, which is calculated in step 7. Thus, the final assessment of all alternatives is completed in this step.

4. Application of measuring the performance of green supply chain management for tire manufacturers

This numerical and real case study is about the usage of the TOPSIS method combined with intuitionistic fuzzy set for the evaluation of drivers of GSCM performance of tire manufacturing companies in the group decision-making environment. These companies as the alternative companies are evaluated and ranked by intuitionistic fuzzy TOPSIS in terms of performance determination of GSCM. Firstly, experts from academic and this specific industrial domain help to determine the necessary drivers of GSCM. **Table 1** presents these five drivers, which are explained in Section 2 as criteria. After pre-evaluation, a committee composed of three decision-makers filled out the questionnaire about green drivers of six tire manufacturing companies competing in the same sector.

Also, the importance levels of ideas among decision-makers have been calculated by using Eq. 3 as the most important detail in this method. The proposed steps in the following are used to reach the best performance of green supply chain management.

Step 1: Determination of the weights of decision-makers.

Linguistic terms in **Table 2** are used to determine both the weights of decision-makers in the group and criteria. In the literature, it is possible to see that different linguistic terms can be applied. However, in this chapter, the linguistic terms, which Boran et al. [53] used in their research, are used. These linguistic terms seem appropriate.

The importance levels and weights of the decision-makers are calculated as in **Table 3**.

C1	Green design
C2	Green purchasing
C3	Green transformation
C4	Green logistics
C5	Reverse logistics

Table 1. Five drivers of GSCM activities.

Linguistic terms	Intuitionistic fuzzy number
Very unimportant	(0.1. 0.9. 0)
Unimportant	(0.35. 0.6. 0.05)
Medium level important	(0.5. 0.45. 0.05)
Important	(0.75. 0.2. 0.05)
Very important	(0.9. 0.1. 0)

Table 2. Linguistic terms for rating the importance of criteria and the decision-makers.

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Decision-maker 1	Decision-maker 2	Decision-maker 3
Very important	Important	Medium level important
0.4062	0.3563	0.2375

Table 3. The importance of decision-makers and their weights.

Decision-makers in this group have different levels of education, different working experiences and company positions.

Step 2: Conversion of decision-makers' evaluation about alternatives into aggregated intuitionistic fuzzy decision matrix.

The linguistic terms for evaluating alternatives on a per-criteria basis by three decision-makers were accepted as presented in **Table 4**.

Table 5 summarizes questionnaire evaluation about criteria of the alternatives by three decision-makers.

Linguistic terms	Intuitionistic fuzzy number
Very good (VG)	(0.75. 0.10. 0.15)
Good (G)	(0.65. 0.25. 0.15)
Fair (F)	(0.50. 0.50. 0.00)
Bad (B)	(0.25. 0.60. 0.15)
Very bad (VB)	(0.10. 0.75. 0.15)

Table 4. Linguistic terms for rating alternatives.

Decision-makers	Alternatives	C1	C2	C3	C4	C5
DM1	A1	G	G	G	G	G
	A2	G	G	G	F	G
	A3	G	G	G	G	G
	A4	G	G	G	F	G
	A5	F	B	F	F	F
	A6	F	F	F	F	F
DM2	A1	G	G	VG	F	G
	A2	G	G	VG	F	G
	A3	G	G	VG	F	G
	A4	VG	G	VG	F	G
	A5	B	F	F	B	B
	A6	F	G	G	F	F

Decision-makers	Alternatives	C1	C2	C3	C4	C5
DM3	A1	G	G	G	F	G
	A2	G	G	G	F	G
	A3	G	G	G	F	F
	A4	G	G	F	F	F
	A5	B	B	F	F	F
	A6	F	F	F	F	G

Table 5. Evaluation of alternatives according to criteria by decision-makers.

In order to ensure no losses occur in the decision-makers' opinion, the IFWA operator is used to construct the aggregated intuitionistic fuzzy decision matrix, shown in **Table 6**, with the help of the evaluation in **Table 5**.

Step 3: Calculation of the weights of criteria.

In the case of decision-making problems, the weight of each criterion is generally different from each other except for some specific evaluations. The most important reason for this is that the significance levels of criteria are different for each decision-maker. If the problem requires the determination of the importance of the decision-makers in a group, as in this study, the linguistic terms, shown in **Table 2**, and Eq. 3, are used together.

In addition, evaluation of decision-makers about the criteria is presented in **Table 7**. By using IFWA, the weights of criteria are calculated as follows:

—	C1	C2	C3	C4	C5
A1	(0.600, 0.250, 0.150)	(0.600, 0.250, 0.150)	(0.662, 0.180. 0.158)	(0.543, 0.377, 0.079)	(0.600, 0.250, 0.150)
A2	(0.600, 0.250, 0.150)	(0.600, 0.250, 0.150)	(0.662, 0.180. 0.158)	(0.500. 0.500. 0.000)	(0.600, 0.250, 0.150)
A3	(0.600, 0.250, 0.150)	(0.600, 0.250, 0.150)	(0.662, 0.180. 0.158)	(0.543, 0.100, 0.150)	(0.578, 0.295, 0.127)
A4	(0.662, 0.180. 0.158)	(0.600, 0.250, 0.150)	(0.643, 0.213, 0.144)	(0.500. 0.500. 0.000)	(0.578, 0.295, 0.127)
A5	(0.364, 0.557, 0.079)	(0.651, 0.562, 0.087)	(0.500. 0.500. 0.000)	(0.422, 0.534, 0.044)	(0.422, 0.534, 0.044)
A6	(0.500, 0.500, 0.000)	(0.538, 0.391, 0.071)	(0.538, 0.391, 0.071)	(0.500. 0.500. 0.000)	(0.526, 0.424, 0.050)

Table 6. Aggregated decision matrix.

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	DM 1	DM 2	DM 3
C1	VI	VI	I
C2	I	VI	I
C3	I	I	I
C4	M	M	M
C5	I	I	M

Table 7. Evaluation of criteria by decision-makers.

$$W = \left\{ \begin{array}{l} (0.876, 0.118, 0.006); \\ (0.820, 0.156, 0.024); \\ (0.750, 0.200, 0.050); \\ (0.500, 0.450, 0.050); \\ (0.705, 0.242, 0.052) \end{array} \right\}$$

Step 4: Construction of aggregated weighted intuitionistic fuzzy decision matrix.

It has become easier to calculate the aggregated weighted intuitionistic fuzzy decision matrix by determining the weight of each criterion. The final weighted combined decision matrix formed by the product operator (IFWA) defined in the intuitionistic fuzzy sets is given in **Table 8**.

–	C1	C2	C3	C4	C5
A1	(0.525, 0.338, 0.136)	(0.492, 0.367, 0.141)	(0.496, 0.344, 0.159)	(0.272, 0.658, 0.071)	(0.423, 0.432, 0.145)
A2	(0.525, 0.338, 0.136)	(0.492, 0.367, 0.141)	(0.496, 0.344, 0.159)	(0.250, 0.725, 0.025)	(0.423, 0.432, 0.145)
A3	(0.525, 0.338, 0.136)	(0.492, 0.367, 0.141)	(0.496, 0.344, 0.159)	(0.272, 0.658, 0.071)	(0.408, 0.466, 0.126)
A4	(0.579, 0.277, 0.144)	(0.492, 0.367, 0.141)	(0.482, 0.370, 0.147)	(0.250, 0.725, 0.025)	(0.408, 0.466, 0.126)
A5	(0.319, 0.609, 0.072	(0.288, 0.631, 0.082)	(0.375, 0.600, 0.025)	(0.211, 0.743, 0.045)	(0.298, 0.647, 0.056)
A6	(0.438, 0.559, 0.003)	(0.441, 0.486, 0.073)	(0.404, 0.512, 0.084)	(0.250, 0.725, 0.025)	(0.371, 0.564, 0.065)

Table 8. Aggregated weighted intuitionistic fuzzy decision matrix.

$r_1'^*$	(0.579, 0.277, 0.144)
$r_2'^*$	(0.492, 0.367, 0.141)
$r_3'^*$	(0.496, 0.344, 0.159)
$r_4'^*$	(0.272, 0.658, 0.071)
$r_5'^*$	(0.423, 0.432, 0.145)

Table 9. Intuitionistic fuzzy positive-ideal solution value.

Step 5: Calculation of intuitionistic fuzzy positive-ideal solution and intuitionistic fuzzy negative-ideal solution.

All the criteria discussed in the problem are beneficial. Intuitionistic fuzzy positive-ideal solution (A^*) and intuitionistic fuzzy negative-ideal solution (A^-) are calculated by taking into consideration the benefit and cost criteria, and shown in **Tables 9** and **10**.

Step 6: Calculation of positive and negative separation measures.

The separation measures between the alternatives and the positive intuitive fuzzy ideal solution and the negative intuitive fuzzy ideal solution are given in **Table 11**.

Step 7: Calculation of the relative closeness coefficient to the intuitionistic ideal solution.

The relative closeness coefficients are determined and shown with positive and negative separation measures in the same table.

Step 8. Ranking the alternatives.

$r_1'^-$	(0.319, 0.609, 0.072)
$r_2'^-$	(0.288, 0.631, 0.082)
$r_3'^-$	(0.375, 0.600, 0.025)
$r_4'^-$	(0.211, 0.743, 0.045)
$r_5'^-$	(0.298, 0.647, 0.056)

Table 10. Intuitionistic fuzzy negative-ideal solution value.

Alternatives	S_i^*	S_i^-	C_i^*
A1	0.061	1.09	0.9467
A2	0.129	1.04	0.8901
A3	0.095	1.06	0.9173
A4	0.127	1.05	0.8915
A5	1.152	0	0.0000
A6	0.768	0.48	0.3856

Table 11. Separation measures and the relative closeness coefficient of each alternative.

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The relative closeness coefficients are used in the order of the alternatives. Six alternatives are ranked according to the descending order of C_i^* value. The alternative with the highest C_i^* value is the best alternative, while the alternative with the lowest value is the last alternative to be selected with the criterion-based evaluation. In this study, the best alternative was selected as alternate 1. While alternate 3 is in the second rank, six different tire manufacturing companies in the form of A1 > A3 > A4 > A2 > A6 > A5 were evaluated.

5. Conclusions and recommendations

In today's business environment, increasing practices of supply chain management with green perspectives have become remarkable and necessary. Thus, successful management of green activities in an uncertain future in a competitive environment has also become important to survive. This chapter explains an intuitionistic fuzzy group decision-making for green supply chain management performances of tire manufacturing companies using intuitionistic fuzzy TOPSIS. Dealing with uncertainties is the subject of this method. In addition to this characteristic, fuzzy average operator helps to combine ideas of decision-makers. On the other hand, if only TOPSIS used to make this evaluation, there would be a different solution. Because, even though TOPSIS has special distance calculations features while calculating the ideal optimal solution, it does not take into account decision-makers' ideas with the different importance levels. All these make the proposed method preferable.

In this chapter, to decide related criteria of GSCM, it is really important to investigate GSCM performances of Turkey's top tire manufacturing companies. This proposed approach can be applied for companies operating in different sectors. In future studies, various multi-criteria decision-making techniques can be combined with intuitionistic fuzzy sets to create hybrid techniques.

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Chapter 8

Supply Chain Innovation with IoT

Yu Cui

Additional information is available at the end of the chapter

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Abstract

In this chapter, we first describe and analyze the evolution of supply chain and the history of IoT technologies' development briefly. And then, we conduct a systematic research on the characteristics of supply chain system in IoT context and analyze how to realize the innovation of supply chain system in IoT context in detail, and on this basis, we propose the architecture of cold chain traceability system. Furthermore, through the decision-making process model for supply chain disruption and establishment of knowledge management system in IoT environment, the competences needed for improving supply chain resilience is reinforced. In the end, a case study is conducted to illustrate the availability and robustness of traceability system in the food supply chan.

Keywords: supply chain innovation, IoT, decision-making process model, traceability system, cold chain

1. Introduction

One obvious characteristic of contemporary social and economic development is the competition, being more intense, and the development of technological progress, being more rapid, prompting enterprises to make a series of changes in the field of logistics and purchasing and more companies to adopt the thoughts and methods of supply chain management (SCM), which not only can reduce the operating costs of enterprises, raise the speed of response to market demand, but also can improve the competitiveness of enterprises in market competition. Nevertheless, there are still certain issues of concern in the operation of supply chain management, such as the low level of intelligentization of SCM, poor visual management, high degree of uncertainty, low automation of certain industries, frequent manual errors, serious industry losses, difficulties in tracing products after sales, etc. The research and development of Internet of Things (IoT) bring new opportunities to the innovation of SCM.

After the advent of computer, Internet, and mobile communications, IoT is another revolutionary development of information industry. From perceptual layer, network layer to application layer, IoT involves a wide range of fields including standards, core technologies, and products, as well as the integration and collaboration among various technologies, systems, products, networks, and applications. With its long industrial chain and wide application, it is indeed omnipresent and all embracing. Therefore, research of IoT has been highlighted in recent years, and its related research and development have also drawn great attention of a variety of countries.

1.1. Research of IoT

In 2005, in "ITU Internet Report 2005: Internet of Things" released by International Telecommunication Union, the concept of Internet of Things is mentioned [1]. According to the report, goal of information and communication technology has developed from connecting anyone with anytime and anywhere to the phase of connecting anything, and the connection of everything forms Internet of Things. In September 2009, the EU Group released the "IoT Strategic Research Roadmap," which considers Internet of Things as an integral part of the future Internet [2]. In 2011, in "Building the Internet of Things using RFID: The RFID ecosystem experience," Welbourne Evan proposed the idea of establishing IoT through RFID, pointing out the importance of RFID in constructing IoT [3].

In 2014, when energy crisis being more and more severe, Roselli explored how to apply IoT technology in the field of energy and develop RFID technology, wireless power transmission, and green electronic products to conserve energy, this can be also referred to in the application of IoT technology in other fields [4]. As network technologies are being applied in more and more ranges, through comparing the security of IoT with traditional network, Jing makes an exploratory analysis on solutions to security issues of IoT, and at the same time, warns the applications of IoT technology, emphasizing that security issues and problems of IoT technology should also be focused [5].

1.2. The evolution of supply chain

The development process of supply chain concept has gone through three phases, which are logistics management phase, value chain phase, and supply chain network phase (see **Figure 1**). With the changes of supply and demand context and continuous advance of information technology, emphasis of supply chain concept has been varied at different stages, and this concept is gradually improved. As shown in **Figure 1**, in this chapter, we use the definition of supply chain network phase, defining supply chain as a value added chain that comprises all the participating node enterprises in supply chain, starting from the supply of raw materials, the manufacturing process, product sales, and to end users. Logistics, information flow, and cash flow are all covered [6].

SCM is to use integrated resource integration concept, advanced information technology, and control technology to manage and coordinate the supply chain network commencing from original supplier to ultimate customer so as to satisfy supply chain members, enhance the efficiency of the whole supply chain, follow the cost-effectiveness principle to the greatest extent, and meet customer demands.

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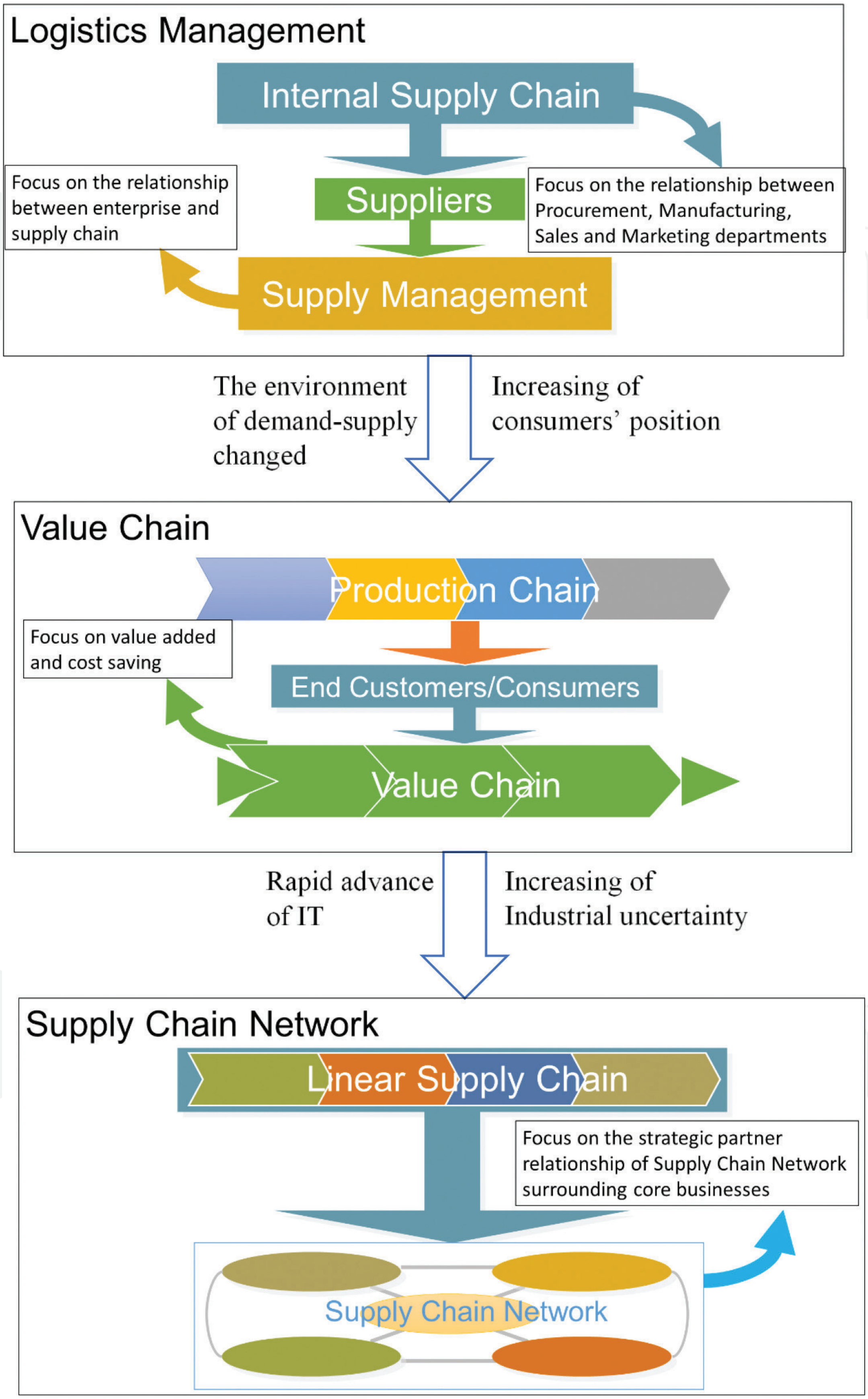

Figure 1. Three phases of supply chain evolution.

The rapid development of new technologies and the emergence of Internet-based e-commerce vitalize supply chain. Enterprises in supply chain start to focus on the improvement of overall performance of the entire supply chain so as to actualize close coordination and seamless connection of node enterprises. With its characteristic endowed by information age, this supply chain enhances the coordination level of supply chain, thereby so-called "collaborative supply chain management" is also paid attention recently [7].

Collaborative supply chain model synthesizes the theoretical research results generated since the birth of the concept of supply chain, and comprehensively reveals the network chain function of supply chain, which comprises all the aspects of product production, including the procurement of raw materials, production and processing, logistics, and sales. The model is an integrated supply chain that manages the synergy of multiple companies.

2. Characteristics of supply chain system in IoT context

IoT, which is also called the third wave of information technology, has induced various new opportunities and changes to SCM and a variety of industries. In especial, it boosts the extension of the function of supply chain; specifically speaking, it provides technical support for enhancing the visualization and stability of supply chain and realizing intelligent management of supply chain.

2.1. Enhancing the visualization of supply chain

One of the main goals of IoT is to improve human perception ability and intelligent processing ability. IoT is able to provide the connection of various objects at any time and any place, and also the status and related information of any object at any time and any location. The perception layer, as the foundation of Inter of Things, is also the basis of IoT-based SCM system in IoT context. For the agricultural supply chain, the introduction of IoT technology intellectual brings new opportunities and changes to intelligent agriculture.

The adoption of RFID tags, wireless sensors, and transmission equipment enables the tracing and visual digital management of single or packaged agricultural products and food. Throughout the entire process, from the production of agricultural products and food to sales, in detail, from the production site to warehouses, from warehouses to tables, intelligent management is able to monitor and realize the digitized and visualized logistics and management of agricultural products and food, improving their quality [8]. In terms of retail supply chain, the application of RFID technology and wireless sensors can provide accurate information regarding the variety, quantity, customer, location, and other related details of products to decision makers in supply chain, enhancing the level of transparency, and visualization throughout the entire process, and more importantly, the whole supply chain (see **Figure 2**). Decision-making entities are able to be aware of the real-time operation progress and make better coordination; accordingly, the efficiency of supply chain is raised to a great extent.

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Layer						
Application Layer	Real -time visible monitor	Production whole-process tracking	Information centralized management	Design materials on spot	Electronic Commerce Platform	Spatial Mapping
Interconnected layer	Data Center		Information Center		Internal Network	
	Cloud computing platform					
Sensing Layer	RFID Tags		Access Gateway		Intelligent Terminal	
	RFID Sensor		Intelligent Device		Motion Sensing Device	

Figure 2. Layer architecture of supply chain system in IoT context.

2.2. Enhancing the robustness of supply chains

Enhancing the robustness of supply chains and lessening the uncertainty of supply chain is one of the important factors to be considered in the establishment of supply chain system [9]. The advent and the development of IoT technology assist in enhancing the robustness of supply chain and lessening its uncertainty. Based on IoT technology, decision-making entities in supply chain can dig and gather data with more accuracy and obtain more precise information, shortening the lead time of expected demand for products or inventory.

At the same time, the application of IoT technology also provides information sharing mechanism to decision-making entities in supply chain, thereby minimizing the bullwhip effect and uncertainty of supply chain, enhancing the robustness of supply chains. In the IoT context, applying IoT technology can make real-time monitoring and decision-making of the whole supply chain throughout the process of supply chains, meanwhile, precise management of the quantity, variety, quality, and batch information of raw materials can be also realized, with accurate information regarding the storage location of raw materials or spare parts being provided. Accordingly, timely replenishment of inventory is performed; hence, shortening of production cycle, decrease of cost, inventory, capital occupation, and eventually supply chain uncertainty can be realized.

Warehouse management plays an important role in supply chains. With the application of IoT technology, the management process of warehouse is simplified. The collection process of information including warehousing, storage location, and quantity is prompt, accurate, and complete, reflecting the real-time inventory status. Furthermore, with the correspondent improvement of space utilization and decrease of cost, management efficiency is raised, thereby the robustness of supply chains is enhanced.

2.3. Realizing supply chain intelligent management

The realization of supply chain intelligent management is an important subject of the supply chain system based on IoT and one of the major changes in supply chain function. To realize the intelligent management of IoT, intelligent platform, which is based on IoT, is significant. The development of IoT technology provides technical support for intelligent management of supply chain. Perception layer is the foundation of IoT. Through the sensor devices of perception layer, the IoT-based supply chain system can continuously obtain information of nodes in supply chain, and dig, classify, integrate, and store relevant data with IoT data processing technology [10]. Eventually, extract useful knowledge and provide timely information regarding supply chain operation status and tendency, and hence realize intelligent decision-making.

First of all, through the installation and application of a variety of sensing devices (such as RFID, sensors, etc.), real-time supply chain operation status can be sensed; when the environment changes, sensed information can be provided to supply chain system timely. Second, the development of wired and wireless network technologies and their integration with internet technologies link the various modules in supply chain system, laying the foundation for prompt and secure transmission of information. Third, the further development of mass data storage technology, data fusion technology, and data mining technology of IoT creates favorable conditions for the development of intelligent decision-making and intelligent control technology, and has turned into an effective guarantee for intelligent management of supply chain. Enhancing the visualization and robustness of supply chain and realizing the intelligent management of supply chain are significant improvements that differentiate supply chain system based on the IoT from traditional supply chain system.

3. Innovation of supply chain system in IoT context

Innovation of supply chain system under the IoT context mainly includes two aspects: innovation of supply chain function and innovation of supply chain process. Along with the continuous development of IoT technology, the function of IoT-based supply chain system has transformed significantly.

In detail, the main functions of traditional supply chain include planning, organizing, coordinating, control, etc. In the context of the IoT, the functions adjust accordingly. In correspondence with this change, supply chain process also needs to adjust. In general, supply chain processes include procurement, production and processing, logistics, sales, and after-sales service process, which also need to be improved accordingly.

3.1. Innovation of supply chain functions in IoT context

3.1.1. Innovations in the planning function

Planning is the basis for the determination of organizational goals. To achieve the goal of supply chain in the context of IoT, in detail, and to improve the level of visualization, transparency, and stability of supply chain, the planning function must be adjusted. In the context of IoT, the application of sensing devices, such as RFID tags and wireless sensors, the integration and adoption of wired and wireless technology and Internet, and the advancement of mass data mining technology can provide information for planning with better precision and speed, thus greatly improving the accuracy of planning.

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On the other hand, the advent of big data perplexes the internal and external environment of supply chain system, greatly amplifying the difficulty in making medium and long-term plan for decision makers in supply chain, decreasing the robustness of supply chain. Accordingly, the planning function needs to be adjusted. In the first place, it is imperative that relevant decision makers in supply chain possess good foreseeability for the development of IoT technology and seize development tendency of IoT accurately. Second, decision makers in supply chain need to dig and collect information to the utmost, so the medium- and long-term plan can be in accordance with the ever developing IoT technology.

3.1.2. Innovation of organizing function

Traditional organizing functions are mainly performed through oral form, written form, telephone, etc. With IoT technology, a variety of new forms can be adopted. For example, with the development of artificial intelligence technology, intelligent robots, as a new type of workforce, are quietly affecting and changing the labor working pattern in manufacturing. The current people-orientated production system will gradually be replaced by intelligent robot-orientated system, which has attracted extensive attention with its advantages such as high efficiency and low cost.

Pattern of this new system transfers from the traditional people-oriented pattern to a new one, which is orientated by intelligent machine, predominantly, and supplemented by manual operation. In the meantime, in the traditional context, organizing function is mainly exerted through the communication or information change among people. While in the context of IoT, the exertion of organizing function not only involves the organizational relationship among people, but also includes the cooperation between people and machines and the coordination of machines. In this way, we can realize the transformation of supply chain functions in the context of IoT.

3.1.3. Innovations of coordinating function

Coordinating function is to promote the consistency of operations through the negotiation and cooperation of all the objects in organization. The fundamental goal of supply chain is to maximize the benefit of the entire chain. Nevertheless, in supply chains, there are always certain conflicts of interests among members of supply chain, impeding the realization of the fundamental goal of supply chains.

According to some scholars, adopting appropriate mechanism design to solve problems, such as asymmetric of information and irrationality of cooperation mechanism among supply chain members, is significant in the realization of fundamental goal of supply chain. IoT technology provide technical support for the maximization of the benefit of the entire supply chain, realizing visual management, and intelligent management throughout the entire supply chain and enhancing the transparency of supply chain, and enabling information sharing among members of supply chain. Accordingly, the resolution of conflicts among the members in supply chain is greatly eased.

Meanwhile, the application of IoT technology also leads to new problems and conflicts of interests among the members of supply chain. For example, uneven investment cost on IoT from decision makers in supply chain, hidden security problems, and issues related privacy protection, which entail ceaseless coordination among members in supply chain and better mechanism design, so the new problem and conflicts of interest appearing in the process of supply chain can be resolved.

3.1.4. Innovations of control function

The essence of control function is to make comparison on the basis of the implementation results with the intended objectives, and then make correspondent adjustments in the light of feedback results continuously. The advent and development of IoT enable the intelligent control, automatic control, and precise control of supply chain. For instance, in the emergency handling system of IoT, robots handling nuclear leakage on site enter designated locations according to instructions, measure parameters related to nuclear leakage through the sensors, and transmit the data to command center. This example indicates that IoT technology has realized extreme perception and control over system processing, providing potent technical support for intelligent control, automatic control, and precise control.

3.2. Innovation of supply chain process in IoT context

In the context of the IoT, with the application of IoT technology (such as RFID, sensor, etc.), accurate information of the whole process including procurement, logistics, production and processing, sales, and after-sales services of goods can be obtained. Meanwhile, cost of procurement, production, storage, and transport and the waste aroused from the procedure can be minimized. The entire logistics process is precisely controlled by information flow. Accordingly, efficiency and profits are maximized.

3.2.1. Innovations in procurement

With IoT technology, intelligent procurement can be realized. In detail, with the acquisition of real-time and accurate delivery information, the waste of fund and time that may result in procurement is greatly decreased, and the stability of procurement is dramatically raised. For example, RFID system can manage the delivery quantity, model, and information of quality provided by raw material suppliers or parts suppliers, and can precisely manage the variety, model number, and batch and production date of raw materials or components. So, replenishment can be conducted in time, and overstock and cash-flow problems are effectively averted.

3.2.2. Innovations in logistics

With the application of IoT, logistics section has changed from the traditional one to intelligent logistics. Basically, the characteristics of intelligent logistics are precise, coordinated, and intelligent. Adopting IoT technology can realize real-time monitoring of the entire process and timely decision-making, inducing the automation and intelligentization of the whole operation process that concludes from procurement, production, and transportation of raw materials.

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Monitoring of warehousing, transfer, distribution, and transportation is actualized through IoT technology. Accordingly, logistics costs such as inventory and transportation, costs are minimized, and waste in links is diminished to a great extent. There is no doubt that the adoption of information streams precisely control the logistics process, thereby maximizing the profit.

3.2.3. Innovations in production and processing

Innovations in this process are mainly reflected in the management of manufacturing equipment, personnel, etc., by means of automatic acquisition technology and intelligent processing technology. Consequently, automation, intelligence, and transparency of production and processing are realized. Especially, in the case of operation of special materials, real-time tracing, and inspecting on operations in extraordinary circumstances. IoT technology enables more precise operation on special materials; while in the meantime, reduces manual errors. And in extraordinary and harsh production and processing circumstances, IoT technology can automate and intelligentize the process, decreasing the hazard caused by manual operations.

In addition, IoT technology allows intelligent and transparent production and real-time monitor on manufacturing information at key positions. Once there is flaw or problem at key position, correction can be made promptly, thereby ensuring product quality.

With the raise of product variety, quantity, and circulation speed, instead of depending on how many goods are stacked, storage efficiency is mainly dependent on precisely seizing the variety, quantity, customer, and stored location information of the stock. IoT technology not only raises the speed of warehousing, delivery of cargo from storage and stock count, but also enhances the level of transparency and visualization of the entire cargo movement process, diminishing or even averting errors in operation, and realizing efficient utilization of storage space, thereby decreasing the cost of storage management and improving the efficiency of storage.

3.2.4. Innovations in sales and marketing

Adopting IoT technology into sales process provides customers with convenient and unusual services. Customers can scan the barcode on shopping cart with their mobile phone to find out the store they are in. Furthermore, they can check the store map and search the products they want with mobile phone.

The application of IoT technology in sales also leads to the emergence of various checkout methods. In detail, cashier can use smart cash register for checkout, and instead of checking and scanning goods one by one for settlement, RFID reader can quickly and automatically read and display the total price of the goods in smart shopping cart. Payment methods for customers to choose from include cash payment, bank card payment, check payment, mobile payment, fingerprint payment, and others. Obviously, automated or intelligent transactions reduce the occurrence of manual errors and related transactional problems. In the meantime, loss of goods that caused by theft etc., can be also reduced; in accordance with it, retail consumption rate is greatly decreased.

3.2.5. Innovations in after-sales service

The adoption of IoT technology in after-sales part contributes to better services provision of enterprises, assists in government regulation, and guarantees the protection of consumers' interests. On one hand, with the information recorded in RFID tag, enterprise can search sold products' manufacturing information such as its time of production, operator, inspector, batch number, serial numbers, etc., so as to resolve after-sale problems and provide better service to customers.

On the other hand, the application of IoT technology guarantees the establishment of a robust product tracing system, which traces from top to bottom. In detail, tracing along raw material suppliers, production and processing companies, logistics companies, vendors or retailers, and finally, the customers. Once problem occurs, problematic link can be found out timely. Government can also perform better regulation. If a consumer purchases defective products, tracing from bottom to top will be conducted for the protection of consumer rights and interests.

3.3. Innovation of supply chain resilience in IoT context

In 2011, Thailand suffered a severe flooding which occurs once in 50 years. Its traditional industrial base—Ayutthaya Industrial Park—was flooded, and nearly 200 factories were closed down. In the same year, Japan's 311 Kanto Earthquake also caused serious losses to the manufacturing industry and numerous supply chain companies in Japan. And recently, scandals involving data falsification in automotive, steel, and carbon fiber have caused great impact on a large number of related supply chain companies, and they are faced with the dilemma of supply chain disruption. In China, Sanlu Milk Powder Incident and Shanghai Fuxi Incident caused by the fact that information on manufacturer's irregular and unethical behavior was not shared with other enterprises in the supply chain in time, giving rise to serious losses to supply chain companies and leading to public's distrust.

In this context, establishing an IoT-based knowledge management system across the supply chain is most essential for improving supply chain resilience. In the following part, adopting a series of procedures undertaken by a supply chain firm of electronic industry when knowledge management system of contingency is started as instance, I briefly introduce in decision-making procedure of different levels, how knowledge management system of contingency operates and supports prompt and accurate decision-making for enterprises when contingency occurs (see **Figure 3**).

3.3.1. Innovations in decision-making process for supply chain disruption

First, according to overall Phronesis of organization proposed by Nonaka, when emergency occurs, knowledge management system of contingency should be launched in different levels of organization [11].

After the occurrence of emergency in Field site phase, staff should go to the scent to investigate and find out the loss, and transfer first-hand data promptly to the administrative phase of the

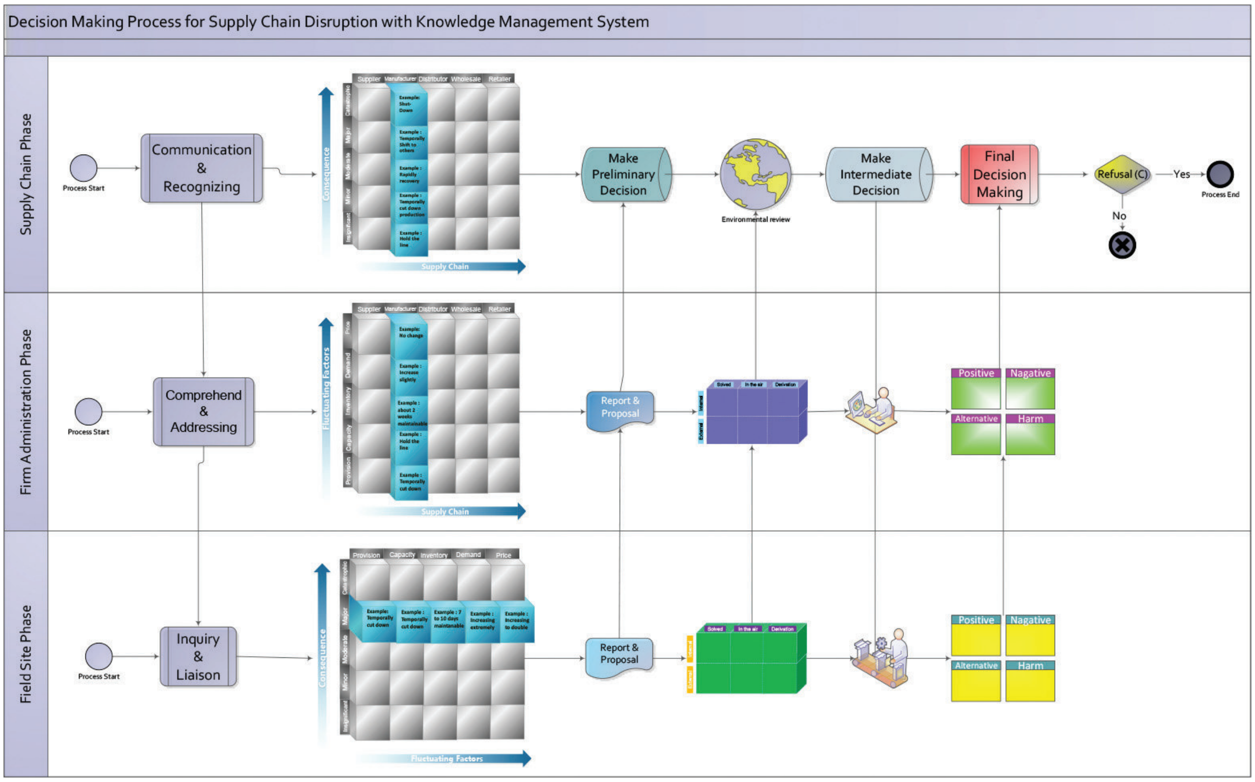

Figure 3. Decision-making process for supply chain disruption.

firm. And after receiving on-site report and being aware of the situation, managers of the administrative phase must manage to resolve the trickiest problems.

On the other hand, the main function of supply chain phase is to actively share first-hand and primary information from the scene. And, in the ever-changing surrounding, recognize the overall situation and make integrated and appropriate arrangement.

3.3.2. Emergency knowledge base system

Nevertheless, to realize the above-mentioned, with the grasp of current situation and swift imagination is far from enough. What we have to establish in advance includes a knowledge base for emergency management (see **Figure 4**).

In this base, previous unexpected incidents and solutions for contingency are stored. For instance, in correspondence with the need of on-site staff, knowledge base can comprehend previous changes of various key factors (provision, capacity, inventory, demand, and price) in different periods through the criticality of incidents (insignificant, minor, moderate, major, and catastrophic). With searching and referring to experience and data, on-site staff can find out the key of problem and make more appropriate predictions.

After making the preliminary decision, various phases successively transfer unsolved problems, make immediate report, and share of problems in the air and problems of derivation. With the summary of entire supply chain and change factors of surroundings and market, intermediate decision is made. Finally, through the conduction of various phases, we

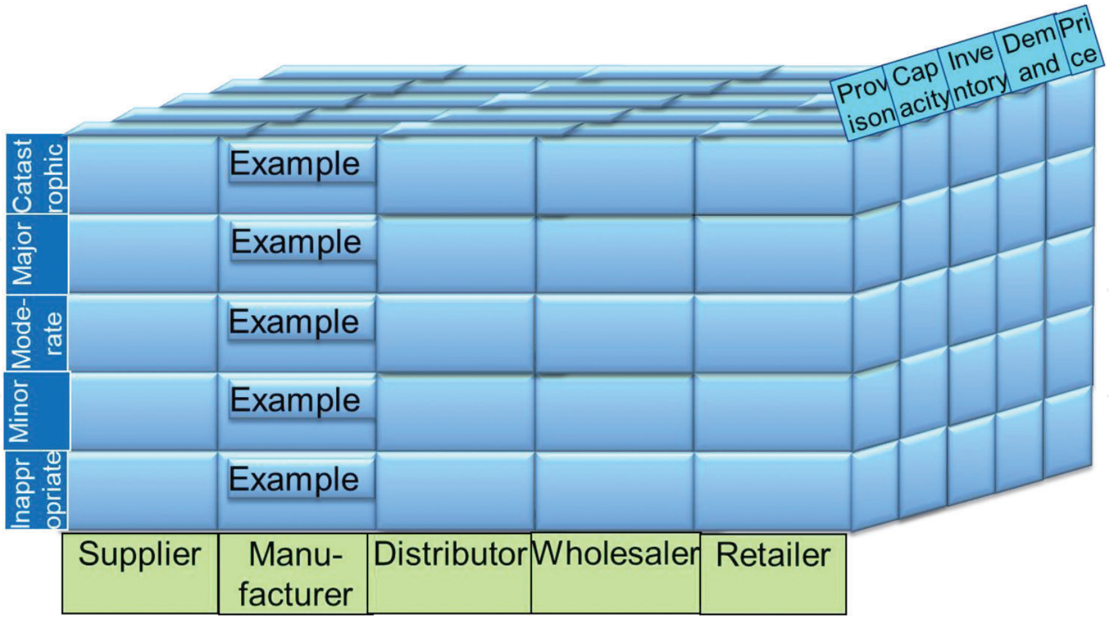

Figure 4. Conceptual scheme of the resilient knowledge-based system.

comprehend and summarize positive, negative, alternative, and harm points, accordingly, the final decision is made.

4. IoT-based food supply chain innovation

The prospect of IoT technology in agricultural industry is extensive. In recent years, IoT and big data has become the pillar of smart agriculture. The application of IoT technology improves the visualization and transparency of food supply chain, reducing the uncertainty of supply chain. Consequently, intelligent degree of supply chains is enhanced.

Food safety has become an issue concerned by the public. Due to the characteristics of fresh food, various chemical and physical changes occur during its circulation process, and any problem in the process may incur issue of food safety. Therefore, one of the most important conditions for ensuring quality and safety of fresh food is to construct a cold chain traceability system.

4.1. Implementation of cold chain traceability system

Cold chain is a special food supply chain, in which temperature is always under control throughout the process from raw materials and resources acquisition, storage, transportation, processing to product sales, and consumption so as to make sure food safety [12, 13]. Food supply chain aims at global resource and raw materials acquisition, global manufacturing, and global sales. Therefore, the carrier of the information must also be globalized (see **Figure 5**).

A set of internationally uniform tracing codes are imperative for food supply and demand network. If all the cold chain enterprises joining in food supply and demand network adopt this set of codes, communication among these enterprises will become smoother, contradictions

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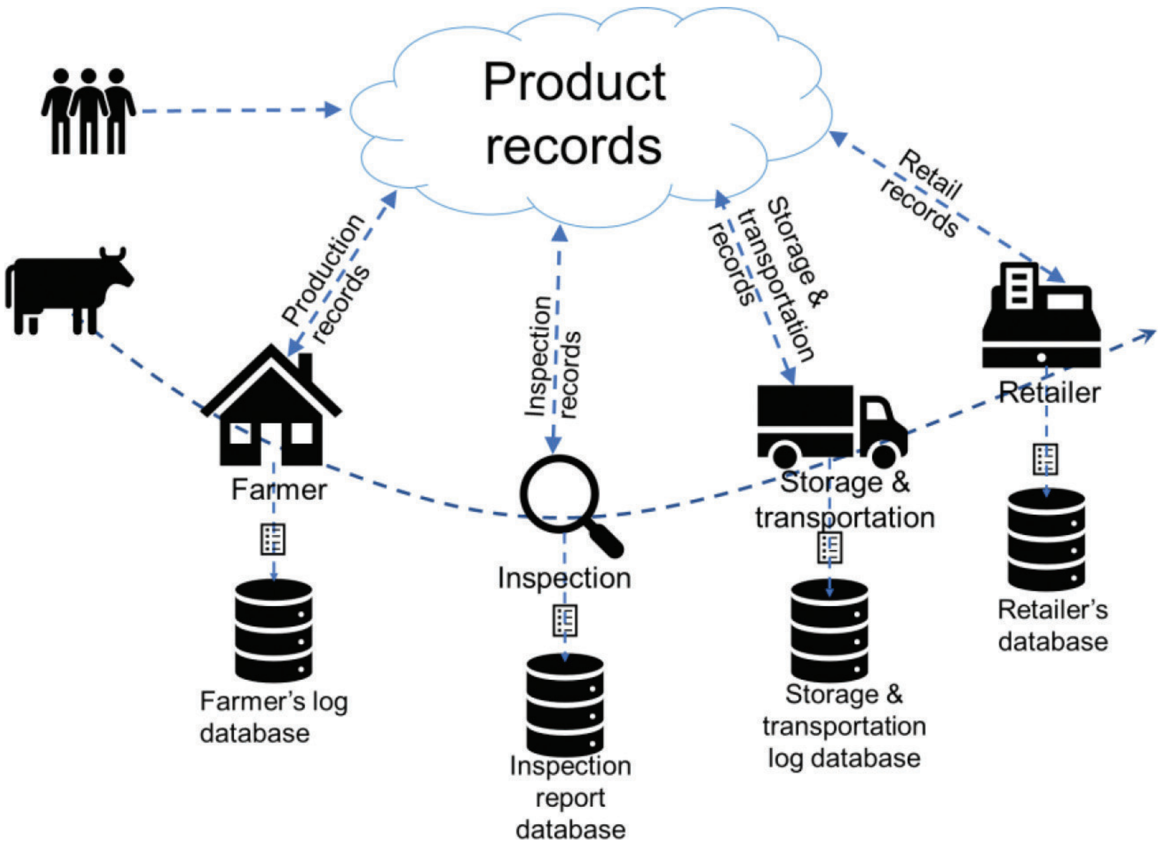

Figure 5. An architecture of cold chain traceability system.

caused by different standards will be reduced; accordingly, tracing efficiency can be improved and tracing cost can be decreased, which also reflects the connectivity and openness of food supply and demand network.

4.1.1. Information system of cold chain traceability system

The establishment of cold chain traceability system is systematical, requiring the integration of information from all the enterprises in cold chain. In this complicated system, information regarding the producers and suppliers of raw materials, producing process, logistics, and consumers are all concluded.

For alliance enterprises in food supply chain, all product information for a single firm is stored in the firm's information system. Moreover, a public cold chain data platform is built for information sharing in the alliance. Once a problem occurs in one enterprise, the source of the problem can be tracked through product information. Meanwhile, other alliance companies can also track the product information to assist the problematic company.

4.1.2. Information system of cold chain traceability system

In food supply chain, a node is an enterprise. Enterprises are connected to each other, representing food supply chain network. Once a part of the supply chain is disconnected, it can be linked through other companies, reflecting the dynamic stability of food supply chain.

What circulate in the circulation line is not only objects, but also the technology, capital, information, management, and human resources, reflecting the versatility of food supply chain. Enterprises of all sizes are welcomed in this network, so the resources will be more abundant and the structure will be more stable, which reflects the openness of food supply chain.

4.2. A case study of cold chain

4.2.1. Cold chain of Xianyi supply chain

Founded in April 2009, Henan Xianyi Supply Chain Co. Ltd., is a temperature control supply chain company in China. Its main business scope include: logistics services, freight forwarding, transit of goods, general cargo, and special transport of goods (containers and refrigeration). In recent years, as the cold chain market evolves continuously, accordingly, the consumers' demand for cold chain products and quality requirement for cold and fresh products also expand constantly. On the other hand, when Xianyi reviews the implementation of China's traceable cold chain system, they find out three main problems: First, information is broken and asymmetric. Second, standards for cold chain are not uniform, with industry standards playing main role, and regulations and constraints are insufficient. Third, cost of traceability is too high. Small and medium enterprises cannot afford the expensive logistics costs, while logistics resources of leading enterprise are vacant in the meantime (see **Figure 6**).

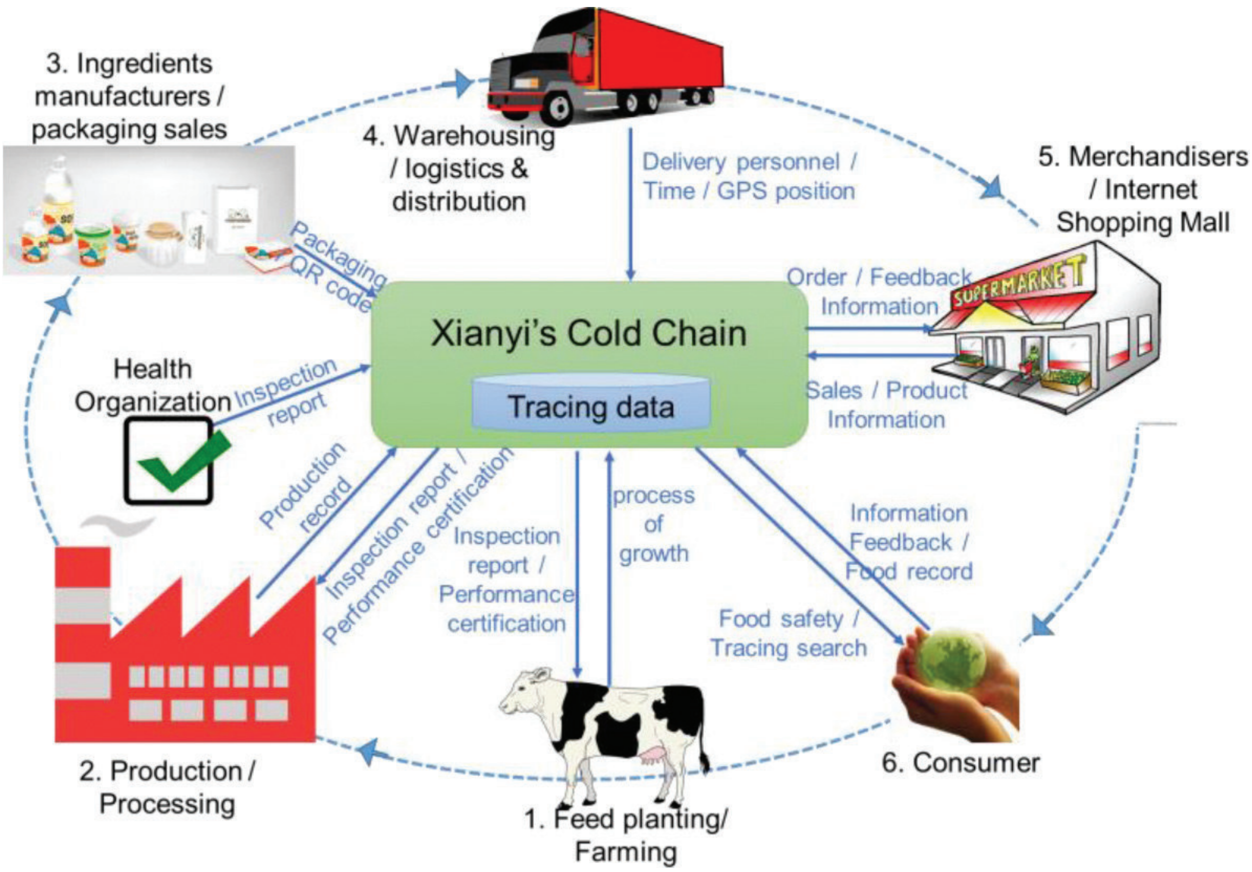

Figure 6. Cold chain of Xianyi supply chain.

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4.2.2. Building smart food supply chain

Xianyi supply chain, which has committed to cold chain logistics for years, with its whole chain and networked temperature control supply chain service system building in the country, accurately capture the demands of various clients and provide customized supply chain service solutions for clients from industrial channels, supermarket channels, food and beverage channels, e-commerce channels, and import channels. With its pointed assistance for customers to optimize their supply chains, efficiency and added value are both enhanced.

With the frequent releases of national policies and the consumers' growing demand for high quality fresh products, Xianyi supply chain actualizes traceable food supply chain service and temperature control visualization of the whole process through in-depth integration of IoT and PaaS information service platform. The company has built a scientific operation management system, established a smart storage and transport system, applied IoT technologies such as RFID tag, GPS, temperature sensor, and driver application to timely monitor the status of fresh products in circulation, including temperature, cargo status and GPS positioning information, food status, and quality information.

5. Conclusions

In this paper, we first describe and analyze the evolution of supply chain and the history of IoT technologies' development briefly. And then, we conduct a systematic research on the characteristics of supply chain system in IoT context and analyze how to realize the innovation of supply chain system in IoT context in detail. And on this basis, we propose an architecture of cold chain traceability system. Moreover, a case study is conducted to illustrate the availability and robustness of traceability system in the food supply chan.

Furthermore, through the depiction and analysis of the decision-making model of how supply chain firms adopt knowledge management system of contingency to make appropriate correspondences when unexpected incidents occur. In this system, knowledge database is the key of contingency management of firms in IoT environment. Therefore, it is necessary to update and improve it unceasingly, and we also need to activate related links and staff of supply chain in share and inspiration so as to truly enhance the key capabilities of supply chain resilience.

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