原料供給者と製品製造者の契約関係を考慮したDEAによるサプライチェーンの評価

Efficiency Evaluation of Supply Chain using Data Envelopment Analysis (DEA) Considering Contract Relationship between Supplier and Manufacturer

Case studies on Thai frozen food industry

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Declaration

I hereby declare that this thesis is my own work and effort and that it has not been submitted anywhere for any award. Where other sources of information have been used, they have been acknowledged.

Muroran, September 2014 CHAOWARAT Woramol

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For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

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Education’s purpose is to replace an empty mind
with an open one.
— Malcolm Forbes

To my beloved family

For their endless love, support and encouragement

Abstract

Background: Efficiency measurement is one of important steps for productive supply chain management (SCM). An efficiency measurement system should be constructed in consideration of practical structure of supply chain. Generally a supply chain structure consists of many types of members, i.e., suppliers, manufacturers and retailers. Each member is connected by relationships such as inter product flow and contact with others. The suppliers can be divided into two types; One is replaceable and another is irreplaceable due to their contract with the suppliers. A contracted supplier has to deliver products to the manufacturers stably under the contract. Whereas non-contacted ones do not have such duty, instead it has a risk to be replaced anytime. It means that non-contracted suppliers need to improve their own efficiencies, otherwise they could be replaced by the manufacturers. Because a supply chain consists of many members, an efficiency of supply chain depends on each member's efficiency. Hence, an efficiency of supply chain in which there are non-contracted suppliers should be considered.

Purpose: The aim of this study is to propose a method of efficiency evaluation of supply chain which consists of different contract types of suppliers.

Methodology: Theoretical models are developed from actual supply chain structure in which different types of suppliers, contracted and non-contracted, are involved. After constructing the models for multiple suppliers supply chain, the proposed models are proved that they are valid and applicable to the potential supply chain. Frozen food industry in Thailand is brought as a case study in this research.

Findings: The results of this research indicate that the proposed models can identify the inefficient supply chains extensively than the existing models. In addition, the proposed models can also provide a primary goal to develop an efficiency of the supply chain by replacing inefficient suppliers.

Theoretical contribution: From a theoretical perspective, the network DEA models with two types of suppliers in a supply chain have been proposed. Regarding to the first sub question, the first DEA model has been built for a situation that contracted and non-contracted suppliers are included in a same chain. For the second sub question, another DEA model has been built for a situation in which all suppliers in chain are non-contracted.

Practical contribution: The proposed DEA models have been applied to measure the efficiency of actual supply chain. Thai frozen food industry is brought as a case study. By using the proposed models, efficiency of non-contracted suppliers is included to examine efficiency of the chain. The proposed models lead us to inspect that which chain is constructed by inefficient non-contracted supplier. After choosing the chain which needs to improve its supplier's efficiency, the efficiency result of chain could be analyzed to understand how the chain efficiency could be changed by improving or changing inefficient non-contracted suppliers to be efficient ones.

Keywords: Efficiency evaluation, Supply chain, Data envelopment analysis, Contract of supplier, Frozen food industry of Thailand

概要

背景： サプライチェーンマネージメントにおいて効率性の測定は重要な段階のひとつである.そして効率測定システムは現実的なサプライチェーンの構造を考慮して構成されるべきである. 通常，サプライチェーンは,サプライヤ，製造業者，小売業者のような複数のメンバーから構成され，各メンバーは生産フローの中で互いに繋がりを持っている．そして例えば農産物サプライチェーンのように複数のサプライヤで構成されるサプライチェーンにおいては，そのサプライヤは製造者と契約を結んでいるものとそうでないものとに分けることができる.契約サプライヤは契約に従って製造業者に安定的に製品供給を行わなくてはならないのに対し，非契約サプライヤにはそのような義務がない. しかしながら非契約サプライヤは,効率を向上させることができなければ他のサプライヤに置き換えられるため，てしまうリストを伴う.従来の研究ではこのような状況は考慮されてこなかった.

目的： 本研究の目的は，異なる契約タイプのサプライヤが存在するサプライチェーンの効率評価手法の提案である.

方法： 契約サプライヤと非契約サプライヤが存在する現実のサプライチェーンの構造に基づいて理論モデルを構築し，このモデルが現実のサプライチェーンに適用可能であることを確かめるために検証を行った．ここでは事例としてタイの冷凍食品生産業を取り上げた.

結果： 提案モデルは現実的な食品サプライチェーン構造において非効率的なサプライチェーンを識別できることが示された．また効率を向上させるために潜在的なサプライヤをサプライチェーンに加えることが可能となった.

理論的知見： 本研究では上記種類のサプライヤが存在するサプライチェーンに対して多段階DEAを適用する手法を提案した．1つ目のDEAモデルは同じサプライチェーンの中に契約サプライヤと非契約サプライヤが存在する状況に適用するものであり，2つ目はサプライチェーンのすべてのサプライヤが非契約である状況に適用するものである.

実践的知見： タイの冷凍食品産業を取り上げ，提案したDEAモデルをサプライチェーンに適用する事例研究を行った．この方法によってサプライチェーンのどこに効率性の低い非契約サプライヤが含まれているのかを知ることが可能になり，さらにそのサプライヤをより効率性の高いものに入れ替えた場合の効率性を分析することも

可能になった．このことから本研究で提案した手法は契約サプライヤと非契約サプライヤが存在するサプライチェーンの効率測定に関する我々の理解を深めたといえる．

キーワード: 効率測定，サプライチェーン，包絡分析法，供給契約形態

Contents

List of Figures

List of Tables

1 Introduction

1.1 Overview

This chapter provides an introduction to the research covered in this study. It starts by explaining backgrounds of this study, followed by the objectives and the research questions. Then, the details of the structure and outline of this thesis are shown.

1.2 Background and Statement of the problem

Supply chain management (SCM) is a principle of management of activities that happen between every member in a chain to maximize customer value and achieve a sustainable competitive advantage [22]. Supply chains consist of business activities needed to design, make, deliver, and use a product or a service that is delivered to the end customers. The concept of supply chain management is defined by Mentzer et al. as follows [71].

> The systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.

The intention of introducing SCM is to satisfy customers' requirements and effective management. The main concept of SCM consists of principles of corporate competitiveness as a foundation of strategy [43, 94]. The competitiveness of a firm depends on the firm's ability to integrate its complex network of business relationships [59]. Since 1990s, supply chains have evolved rapidly showing an exponential growth in papers in different journals of interest to academics and practitioners. Researches in these areas mainly focus on improving the efficiency and competitive advantage of manufacturers [8]. A firm's performance depends on its members in the supply chain, and simultaneously the performance of a supply chain will be determined by the successful of supply chain members' cooperation [28].

Regarding to supply chains consist of many members, to measure an efficiency of the chain is challenging because of its difficulties to identify an efficiency result of a chain by considering all members. In order to assess a supply chain, an adequate performance evaluation system is required because it helps to indicate an efficiency of the supply chain and find out its weakness which leads improvement [14]. Besides, performance measurement helps managers to make trade-offs between profit and investment [75]. Regarding to SCM concepts which concerns about cooperation between members in a chain, for effective SCM, total efficiency of system should be measured as well as each member performance [49]. A well-defined supply chain measurement system increases the chance for success by aligning processes across multiple members [59].

A structure of supply chain is different because it is constructed based on product's characteristic and production. Generally a supply chain structure consists of many types of members, such as, suppliers, manufacturers, transporters and retailers. Each member is connected by relationships such as inter product flow and contact with others. Therefore, the suppliers in a chain can be divided into two types, i.e., contacted one and non-contracted one [19]. Contracted supplier has to produce materiel for the manufacturer stably under the contract. Whereas non-contacted ones do not have such duty and it can be replaced anytime. It means non-contracted suppliers need to improve their efficiency or the manufacturers could stop the order to the supplier.

A chain may consists of only one type (contacted or non-contracted one) or the both types of suppliers. A chain that consists of the both types of suppliers is shown in fig. 1.1. Both suppliers consume inputs to produce intermediate products and deliver them to the manufacturer. After receive intermediate products from suppliers, the manufacture uses the products to produce outputs and deliver to next members in the chain. As mentioned before, a contract system has brought in a supply chain, an efficiency of non-contracted supplier is focused. In the case that the non-contracted supplier is inefficient, this supplier has to improve itself to be efficient or will be changed by the manufacturer. Hence, to improve an efficiency of inefficient supplier, all possible suppliers in measurement are considered as options to be changed. As shown in fig. 1.1, each of the non-contracted suppliers (A,B,C) is considered to be replaced.

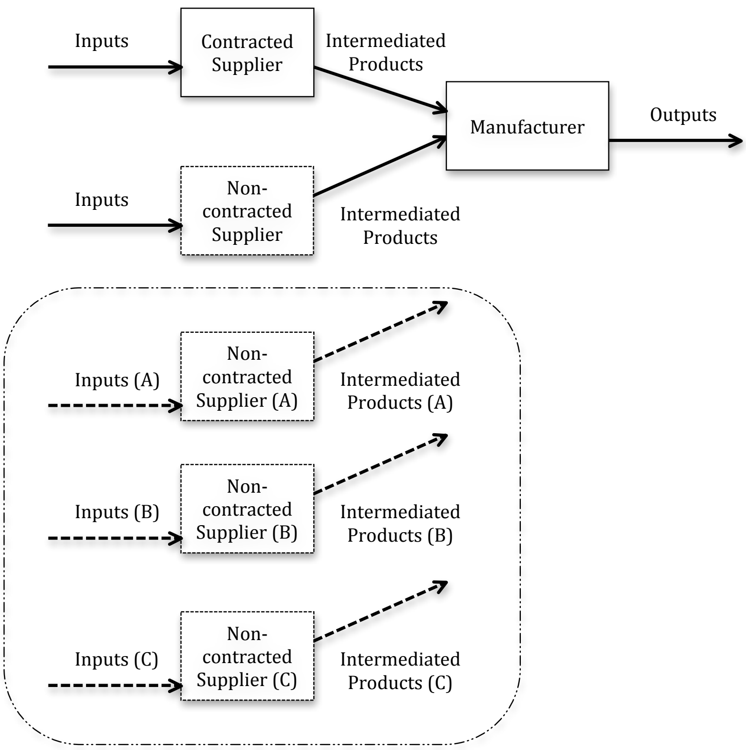


Figure 1.1 – Supply chain structure with contracted and non-contracted suppliers

However, in traditional way of using the network DEA model, the manufacturer or assessor needs to change the non-contracted supplier and evaluate the efficiency of chain manually. Fig.1.2 shows the above mentioned chain. In this chain, non-contacted supplier B of each chain (B_1, B_2 and B_3) are changed into an in-considering chain. The chain in which has been changed its non-contracted supplier is called a virtual chain. In an efficiency measurement, all virtual chains represent all possible chains which can be created. These virtual chains are evaluated their efficiency and compared with existed chains. For example, in chain 1, virtual chains which consist of all possible non-contracted suppliers, (B_2 and B_3), are created in measurement as shown at the lower side of Fig 1.2. Each virtual chain's efficiency is compared and the most virtual efficient chain structure is chosen. Finally, the most efficient virtual chain is compared with other chain in an efficiency measurement.

In a chain in which there are many changeable suppliers, there are more suppliers that can be changed to create possible virtual chains and compare supply chain's efficiency of these virtual chain with current efficiency. Due to this, it may cause a complicatedness to create all possible virtual chains.

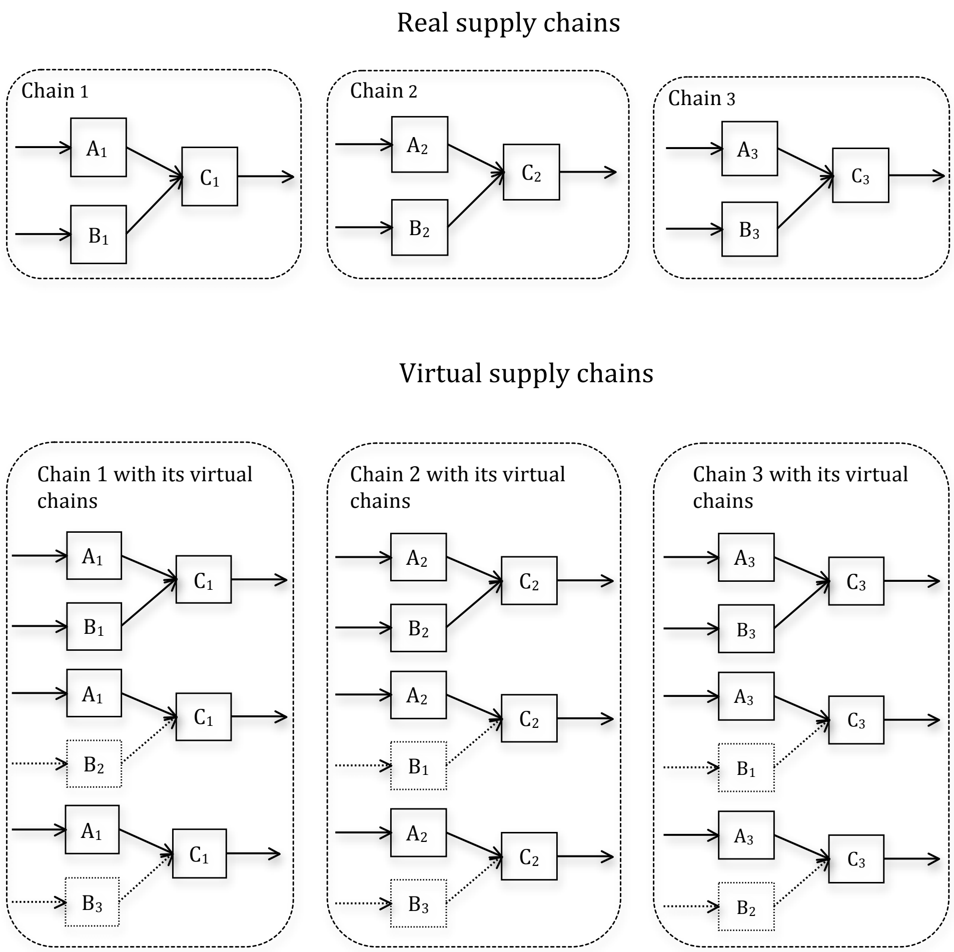


Figure 1.2 – Real supply chain and virtual supply chain

According to above discussion, to use the traditional network DEA, it may causes difficulty in the case that the virtual chain is considered in an efficiency measurement. Therefore, in this research, a method of efficiency measurement to avoid this problem is considered.

1.2.1 Objective and Research Question:

From the above mentioned, the efficiency measurement system which allows us to consider virtual supply chain efficiency with considering to change non-contracted suppliers is required. The objective of this research is:

To contribute to the efficiency evaluation method with network DEA models

that consists of different contract types of suppliers.

To achieve the aim of this thesis, then many questions are arisen, the research questions are follows:

Main Question 1 How to improve the traditional network DEA for generating virtual chain by changing in efficient non-contracted supplier with efficient one?

Sub Question 1. How to improve the network DEA model for the situation that all suppliers under consideration are non-contracted?

Sub Question 2. How to improve the network DEA model for the situation that some suppliers under consideration are non-contracted?

From the above questions, an alternative DEA model is required. The alternative DEA models are a major contribution of this thesis. In order to achieve this, mathematical proof is needed to incorporate to the models.

Main Question 2 How can the proposed DEA models measure the efficiency of a potential supply chain?

This research question is equally important because it links the proposed models to practical supply chains. To answer this question, the proposed DEA models are applied to measure the efficiency of actual supply chains to show their applicability. Case studies approach are utilized to obtain an answer to this question.

1.2.2 Research contributions

This thesis aims to develop a method to evaluate efficiency of supply chains with considering contract relationship among members besides inter production flows which connect with others. The theoretical and practical contributions of this thesis can be summarized as follows.

Theoretical contributions

From a theoretical perspective, network DEA models with two types of suppliers of a supply chain are proposed. Regarding to the first sub question, the first proposed DEA model has been built for a situation in which contracted and non-contracted suppliers are included in a same chain. For the second sub question, the second proposed DEA model has been built for a situation that all suppliers in chain are non-contracted.

Practical contributions

The proposed DEA models have been applied to measure the efficiency of actual supply chain. Thai frozen food industry is brought as a case study. By using the proposed models, efficiency of non-contracted suppliers is included to examine efficiency of the chain. The proposed models lead us to inspect that which chain is constructed by inefficient non-contracted supplier. After choosing the chain which needs to improve its supplier's efficiency, the efficiency result of chain could be analyzed to understand how the chain efficiency could be changed by improving or changing inefficient non-contracted suppliers to be efficient ones.

1.3 Structure and Outline of the Thesis

This thesis consists of six chapters in which shown in Fig. 1.3.

Chapter 1 : A main area of study which is addressed in this chapter. Definitions of key concepts are given for the common understanding of an interested area. After a broad overview of the thesis has been given, a focus of this thesis and research questions are identified.

Chapter 2 : The more extensive reviews of the key concepts specified in Chapter 1 is provided. It shows previous methodologies and results from the related literature in order to identify research gaps. SCM, supply chain performance, DEA and applications of DEA on SCM are reviewed.

Chapter 3 : Outline of this thesis is presented. There are details of each specific research phases and the research processes. The development of the network DEA models to consider non-contracted suppliers are shown. Research limitations are also discussed in this chapter.

Chapter 4 : The proposed DEA models which are constructed based on characteristics of non-contracted suppliers are presents. The proposed models obtains two types of situations in a supply chain. The first model represents the situation in which all suppliers are non-contracted. The second model represent the situation in which only some suppliers are non-contracted. The proposed models are applied for different situations in the following chapters.

Chapter 5 : An applicability of the proposed models to measure an efficiency of an actual supply chain from Thai frozen food industry is exhibited. The models are also applied to an actual data to measure an efficiency of a frozen shrimp industry and a frozen vegetable industry.

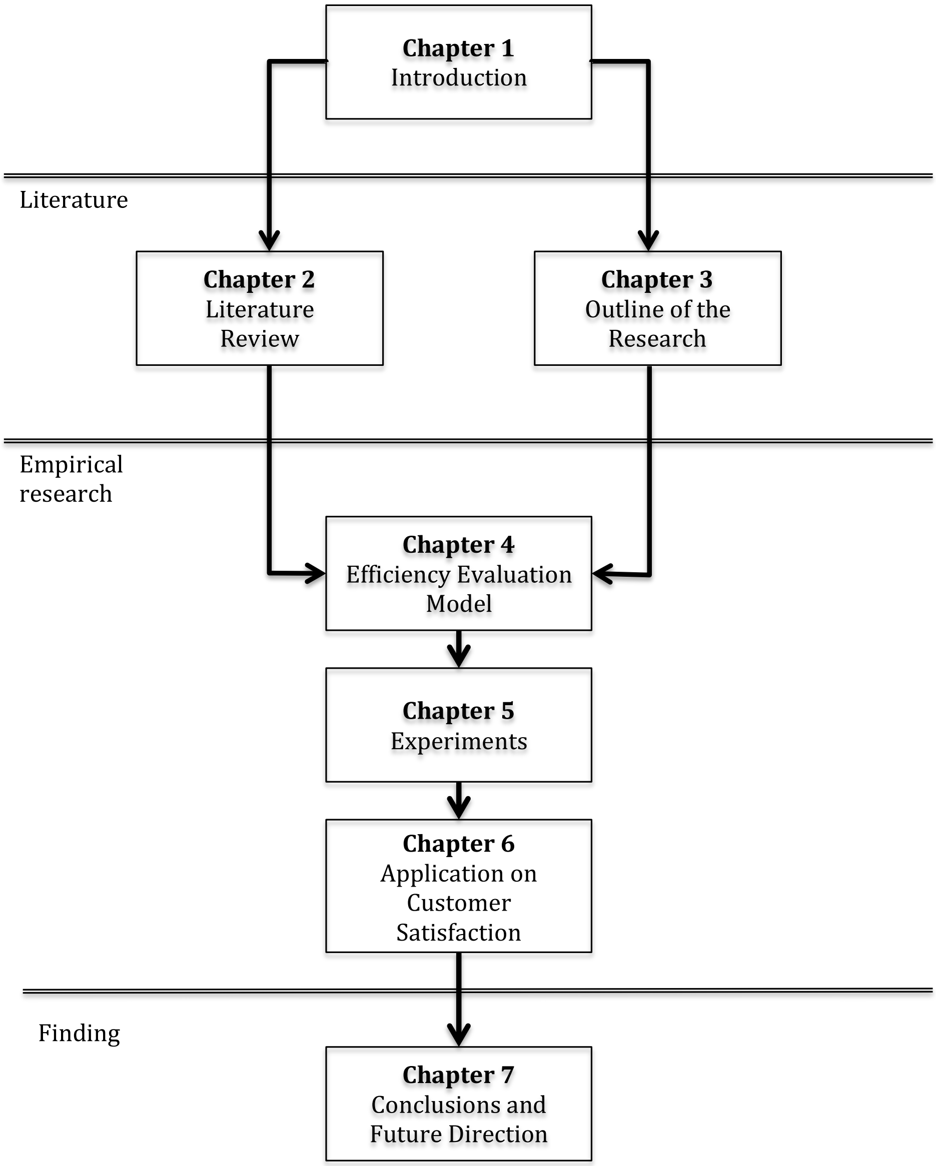


Figure 1.3 – Thesis structure and outline

Chapter 6 : An applicability of the proposed DEA models to analyze an efficiency of supply chain consider customers' satisfactions is presented. In order to show the ability of the models and the results is discussed.

Chapter 7 concludes the thesis by referring back to the research questions. Research contributions are highlighted. Future research are identified.

2 Literature Review

2.1 Introduction

In this chapter, key concepts and approaches which are used in this study is described. The following three topics are mentioned; the first one is SCM and its efficiency measurement, the second one is the fundamental of DEA, and the last one is application of DEA on SCM. The review starts with a discussion of supply chain management, including definitions and fundamental, advantages of supply chain management. The review then considers supply chain performance and efficiency. Besides, the review focuses on DEA technique that involves the issues of its basic and evolution. Furthermore, this chapter also reviews the applications of DEA on supply chain.

2.2 Supply Chain Management (SCM) and its performance measurement

In this section, the definitions and concepts of supply chain management its performance, and efficiency measurement are shown.

2.2.1 Fundamental of SCM

The term 'Supply Chain' was introduced by Keith Oliver back in 1982 [77]. Oliver, a consultant at Booz Allen Hamilton, coined the term during an interview for the Financial Times in 1982. Later in 1998, Christopher defined the terms of supply chain as the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer [34, 80].

Various definitions of the word of supply chain have been offered in the past several years as the concept has gained popularity. Ellram and Cooper [42] used the definition: “Supply chain management is an integrating philosophy to manage the total flow of a distribution channel from supplier to ultimate customer.” The Supply Chain Council [2] defines the definition: “The supply chain - a term increasingly used by logistics professionals - encompasses every effort involved in producing and delivering a final product, from the supplier’s supplier to the customer’s customer. Four basic processes - plan, source, make, deliver - broadly define these efforts, which include managing supply and demand, sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, and delivery to the customer.”

Rhonda [68] stated as:

> all the activities involved in delivering a product from raw material through to the customer including sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, delivery to the customer, and the information systems necessary to monitor all of these activities.

Li [62] explained that:

> SCM is a set of synchronized decisions and activities utilized to efficiently integrate suppliers, manufacturers, warehouses, transporters, retailers, and customers so that the right product or service is distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying customer-service level of requirements.

Mentzer [71] defined supply chain management as:

> a systemic and strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.

The supply chain is a network of firms, workers, technology, activities, information and resources that are implicated in transferring products or serving services from the suppliers to customers. The basic idea behind the SCM is that the firms and corporations involve themselves in a supply chain by exchanging information regarding market fluctuations and production capabilities [15, 47, 55]. Some reviews on current supply chain imply the delivery of capital projects has identified many areas for improvement, such as process re-engineering, suppliers' inventory management, collaboration, trust, communication, organizational structure, e-business deployment, and many other issues [101].

From these definitions, a summary definition of the supply chain can be stated as: all activities which include fulfilling customers' requirements and archiving goal of management. Then I can explain it as the activities, which are influenced by the conduct of supply chain to gain desirable outcomes.

Supply chain contracts are also useful tools to enable the several supply chain members of a decentralized setting to behave coherently and efficiently coordinate with each other. The contract can be defined as an agreement between the two parties. The contract is a set of many clauses, that provide suitable information and incentive mechanism to guarantee all the firms in supply chain to achieve coordination and optimize the SC performance [8].

Structuring the supply chain requires an understanding of the demand patterns, service level requirements, distance considerations, cost elements and other related factors. It is obvious to notice that these factors are highly variable in nature and this variability needs to be considered during the supply chain analysis process. Moreover, the interplay of these complex considerations could have a significant bearing on the outcome of the supply chain analysis process [20]. There are six key elements to a supply chain:

Production : represents what customers want and market demands. It also considers focus on capacity, quality and volume of goods, keeping in mind that customer demand and satisfaction must be met.

Supply : means a stage of finding facility or facilities and materials regarding the first element.

Inventory : In this topic, inventory and how much product should be in-house are determined.

Location : In this topic, the placement of production plants, distribution and stocking facilities, and placing them in prime locations to the market served are focused.

Transportation : represents how to deliver products to customers.

Information : Supply chain principle is co-operation between members. Thus, effective supply chain management requires to obtain information from the point of end-use, and linking information resources throughout the chain for speed of exchange.

Today's business environments are typically seen becoming inherently more unstable due to fast-changing market conditions, customer demands, actions of competitors, and so on [18]. According to high competition in business environment, the organizations have to improve their performance and develop competitiveness. In the changing competitive environment, it is a necessity for suppliers to develop organizations and facilities more flexible and responsive than the existing ones [48].

To achieve improved competitiveness, many firms have utilized SCM to increase organizational effectiveness and achieve such organizational goals as improved customer value, better utilization of resources, and increased profitability [60].

To manage a supply chain efficiently, improving supply chain performance has become one of the critical issues to develop competitive advantages of companies [16]. In this context, continuously improving performance has become a critical issue for most suppliers, manufacturers, and the related retailers to gain and sustain competitiveness and also for researchers and practitioners to research and to study for presenting the most suitable performance system. The overview of supply chain performance and efficiency is presented in next sections.

2.2.2 Supply chain and its performance measurement

The efficiency or performance can be clarified by using the degree to how well the supply chain can fulfill end user requirement [91]. And performance measurement is defined as a process of quantifying an effectiveness and efficiency of actions according to activities in supply chain [75]. The member in a supply chain will be able to make good decisions for its own operations. This will also tend to maximize the profitability of the supply chain as the whole supply chain [54]. According to this fact that information is the connection between all of the activities in a supply chain. Therefore in the efficiency measurement of supply chain should involve the information or feedback criteria in evaluation system as well.

With a fast change happening in the world, performance measurement plays an important role in SCM initiative and improvement [1]. Because it leads to set objectives, goals, evaluating performance and determining future courses of actions. In recent years, performance measurement and indicators have been acquired much attention from many researchers. Gunasekaran [48] summarized why he need to study the measures and indicators in two reasons: lack of a balance approach and lack of clear distinction between metrics at strategic, tactical and operational levels. The results of this research show that the improvement of the performance measurement program should be associated and committed to

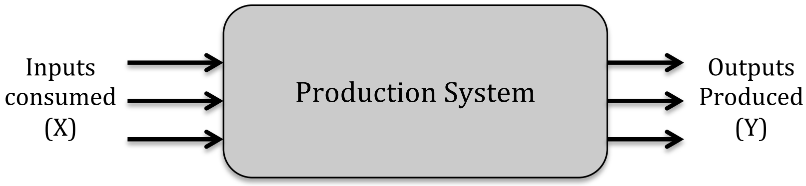


Figure 2.1 – Traditional DEA structure

common goals and tailored to varying needs of members in chain.

2.3 Data Envelopment Analysis (DEA) and its evolution

Original DEA method, proposed by Charnes et al. [24] , is order to evaluate an efficiency of units. DEA is a linear programming, non-parametric technique. The original motivation for DEA was to measure the relative efficiency of peer decision making units (DMUs) with multiple inputs and outputs [4, 89]. DEA aims to produce the maximum outputs or use the minimum inputs by treating a DMU as a black box, i.e. the internal structures are ignored [38, 50]. The basic idea of DEA is using input and output values of other units tries to construct a hypothetical composite unit out of existing units. The basic structure of DEA is shown in fig. 2.1. The Charnes-Coo-per-Rhodes (CCR) model is formulated as a task of fractional programming in the following form for the selected entity o:

$$\begin{aligned} \text{maximize} \quad & \frac{\sum_{l=1}^{L} \mu_l Y_{l0}}{\sum_{i=1}^{I} \nu_i X_{io}} \\ \textit{subject to} \quad & \frac{\sum_{l=1}^{L} \mu_l Y_{lj}}{\sum_{i=1}^{I} \nu_i X_{ij}} \leq 1 \qquad j = 1, \dots, n \\ & \mu_l, \nu_i \geq 0 \end{aligned}$$

where

X_{ij} : Vector of i-th inputs for j-th DMU.

ν_i : The weight to be determined of i-th inputs.

Y_{lj} : Vector of l-th outputs in j-th DMU.

μ_l : The weight to be determined of j-th outputs.

n : The number of DMUs.

I : The number of inputs.

L : The number of outputs.

The efficiency of one decision-making unit o is defined as a ratio of the weighted sums of their outputs and the weighted sums of their inputs. The importance of each input and output is shown by $[v_i]$ and $[\mu_l]$.The above model is nonlinear and non-convex, with a linear and fractional objective function and linear and fractional constraints. Using a simple transformation developed by Charnes and Cooper [24], the above model can be reduced to the LP form (the Primal CCR model) so that the LP methods can be applied.

$$\begin{array}{lll} \text{maximize} & \sum_{l=1}^{L} \mu_l Y_{lo} & \\ \textit{subject to} & \sum_{l=1}^{L} \mu_l Y_{lj} - \sum_{i=1}^{m} v_i X_{ij} \leq 0 & j = 1, \ldots, n \\ & \sum_{i=1}^{I} v_i X_{io} \leq 1 & j = 1, \ldots, n \\ & \mu_l, v_i \geq 0 & \end{array}$$

The above model can be also solved in dual form. The dual model for a given unit using input and output values of other units tries to construct a hypothetical composite unit out of the existing units. If it is possible, the given unit is inefficient, otherwise it is efficient and lies at the efficiency frontier [69]. The dual model is expressed as;

$$(CCR) \quad \begin{array}{lll} \text{minimize} & \theta & \\ \textit{subject to} & \theta X_{io} - \sum_{j=1}^{n} \lambda_j X_{ij} \geq 0 & i = 1, \ldots, I \\ & \sum_{j=1}^{n} \lambda_j Y_{lj} \geq Y_{lo} & l = 1, \ldots, L \\ & \lambda_j \geq 0 & \end{array}$$

By evaluating the efficiency of unit DMU_o, the above model seeks a virtual unit, which characterized by inputs $\lambda_j X_{ij}$ and outputs $\lambda_j Y_{rj}$. $\lambda_j X_{ij}$ and $\lambda_j Y_{rj}$ are a linear combination of inputs and outputs of other units of the population. They are better that the inputs and outputs of unit DMU_o which is being evaluated. For inputs of the virtual unit $\sum_{j=1}^{n} \lambda_j X_{ij} \leq X_{io}$ and for outputs $\sum_{j=1}^{n} \lambda_j Y_{rj} \geq Y_{ro}$. Unit DMU_o, is rated efficient if no virtual unit with requested traits exists or if the virtual unit

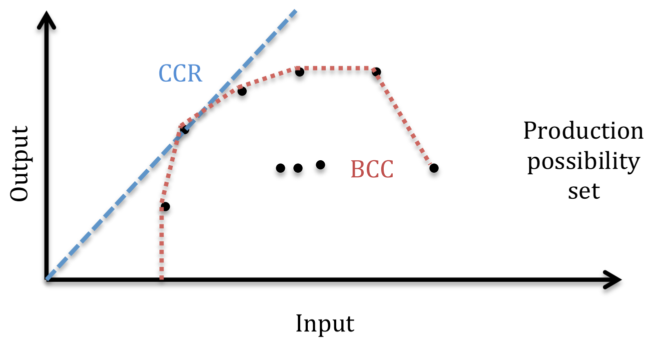


Figure 2.2 – Production frontier of the CCR and BCC models

is identical with the unit evaluated, e.g., $\sum_{j=1}^{n} \lambda_j X_{ij} = X_{io}$ and $\sum_{j=1}^{n} \lambda_j Y_{rj} = Y_{ro}$. If DMU_o is efficient, θ is one. For inefficient units, θ is less than one. This value shows the need for a proportional reduction of inputs for unit DMU_o to become efficient [92]. The CCR models assume Constant Returns to Scale (CRS) which means that if there is an increase in the inputs, the results in a proportion increase in the output level as well, for example, reducing input while remains output unchanged.

Since DEA techniques have been introduced, various extensions of the CCR models have been proposed. In 1984, Banker et.al.[11] have been introduced an extension of the original CCR models which called BCC models. The BCC models assume Variable Returns to Scale (VRS). The VRS models reflect the fact that production technology may exhibit increasing, constant and decreasing returns to scale. The BCC and CCR models are similar except the BCC models that includes the convexity conditions $\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0, \forall j$. The comparison of the CCR and BCC models frontier is shown in Fig. 2.2.

The previous two efficiency models are redial projection constructs. In 1985, Charnes et al. [23] introduced the additive or Pareto-Koopmans (PK) model to extend and combine both input and output orientations [37]. The another important extension for DEA is a Slack-Based Measure (SBM) which has been introduced by Tone [90]. This model is proposed to deal directly with the excess inputs and the output shortfalls of the DMU. Besides, the Russell measurement model, has been presented by Fare and Lovell [45] is equivalent to Tone's SBM. All above model is ignored internal processes. There are many major researches thrusts in DEA more over the three decades [37]. DEA was utilized into many sections such as electric industry [7], banking [61], insurance [30] and even mobile phone brand [13]. However the traditional DEA model and its extension models had limitation to deal with complex structure then multilevel models were presented to fix this problem. In 1996, Fare and Grosskopf [44] presented the network DEA. This ap-

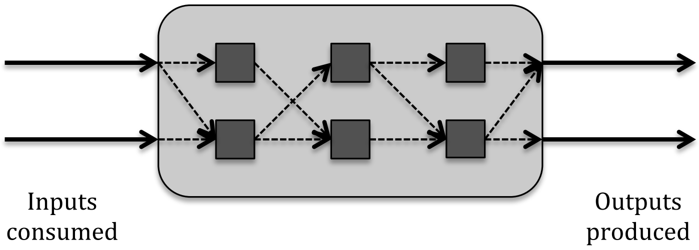
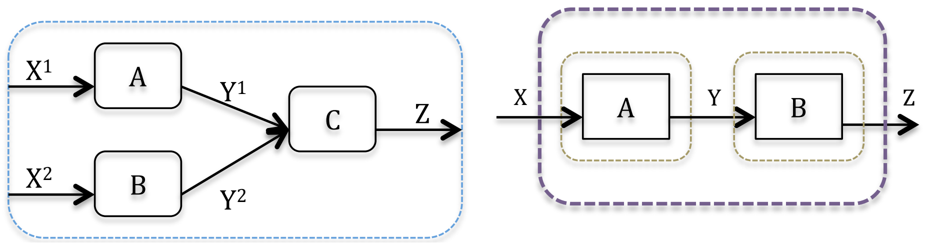


Figure 2.3 – Multi-stages structure

proach allows one to examine more detail the inner workings of the production process, potential leading to a greater understanding of that process [37]. This was the beginning of many researches on multi-stages as shown in Fig. 2.3 and also on supply chain structure. In next section, applications of DEA on supply chain performance and efficiency is described.

2.4 Applications of DEA on Supply chain performance

For supply chains DEA models, it was started by Seiford and Zhu in 1999 [85]. Zhu [102] proposed a DEA-based supply chain model to both measure the overall efficiency, and its members. Besides, the game theory concepts were applied to model of Liang et al. [63]. They claimed that the traditional DEA models cannot be directly applied to evaluate multi-member supply chain operations. Their models, which use game theorem, become tools for the managers in monitoring and planning their supply chain operations. This model can significantly aid in making supply chains more efficiently. Because of this model, all outputs of the first stage are the only inputs to the second stage. Hence, in 2009 Chen [30] examined relations and equivalence between two existing DEA approaches that address measuring the performance of two-stage processes. Subsequently, in 2012, Li [61] extended this model by assuming that the inputs to the second stage include both the outputs from the first stage and additional inputs to the second stage. All above mentioned models, they have shared the same production possibility set as in Fig. 2.4 (a). In Fig. 2.4, dashed lines squares indicate production possibility set. In their models, an efficiency score is measured by existed supply chain. In 2009, Yang et al. [99] introduced the supply chain DEA model under consumption that every members in a chain can be replaced by introducing separate production possibility set concept as in Fig. 2.4 (b). Yang's model focuses on single supplier and single manufacturer supply chain. First, each member's efficiency is allowed to measure and compare with others. Then virtual supply chain is constructed by efficient members. Finally the chain efficiency is measured by merging all member as one chain.



(a) Network DEA [26, 30, 31, 63, 102] (b) Yang's model [99]

Figure 2.4 – DEA models for supply chain

Zha Yong [100] presented the two-stage BCC model by using a geometric-mean method for cooperative efficiency evaluation. The BCC model was chosen to consider the influence of both technology efficiency and the returns to scale efficiency. Additionally, to deal with the dynamic effect on network, a network-DEA with Sub Decision-Making Units (SDMUs) within a DMU was provided to analyze performances in a dynamic production network [29]. In 2013, Lotfi et al. [66] reviewed the state of the art in network DEA modeling. In particular two-stage models, along with a critical review of the advanced applications that were reported in terms of the consistency of the underlying assumptions and the results derived. Besides, they also proposed the common-weights DEA method to deal with total weights flexibility in DEA.

From previous researches, they shows that an important area of development during the recent years has been devoted to applications wherein DMUs represent two-stage or network processes [36]. Afterward, the study of agile supply chains by Wu [95] in 2011 proposed an approach of DEA for partner selection and decision making which able to meet the combination of qualitative and quantitative objectives that are typically found in partner selection problems in practice. Zhu et al. [103] applied network DEA method for evaluating eco-efficiency of products. They claimed that it could distinguish differences in the eco-efficiency of products at the different stages. Besides, it could provide a better discrimination among pesticides while being compared with single-stage, case study on China's pesticides.

Ebrahimnejad et al. [40] utilized a three-stage DEA model with two independent parallel stages linking to a third final stage for banking industry. They claimed that their model can deal with changing the intermediate inputs to outputs. Huang et.al. [53] modified two-stage DEA model that allows multiple efficiencies to be calculated in the unique stage. In this research, the concept of intermediate input was introduced with using 58 Taiwanese international hotels. Egilmez et al. [41] used single-stage DEA model for sustainability assessment in SC, Food manufacturing sectors of United States was brought as case study. Wanke and

Barrosb [93] also provided a two-stage DEA in application for Brazilian banks.

Besides, the stage of model, an internal structure for supply chain should be focused as well. Thus, Network DEA model for supply chain performance evaluation by Chen [27] was presented. Chen introduced three different network DEA models under the concept of (1) centralized which represented the supply chain that is supervised by a single decision maker who can arrange the supplier and manufacturer operations to maximize the whole supply chain efficiency, (2) decentralized which stand for supply chain that has its own incentive and strategies and (3) mixed organization mechanisms in term of two-stage model.

As for supply chain management, DEA was applied in many areas. It was also used in supplier selection and evaluation in a supply chain as well [32]. In Chen's research, DEA was used to evaluate performance of the supplier, prior to the suppliers. A value chain concept was also used in DEA to evaluate the performance of purchasing and supply management [84]. The proposed model in this study provides a single measure of performance evaluation, which can be used to benchmark with peer companies within the industry at a given point in time as well as with own performance at different points in time. Chen [27] used the two-stage network DEA model to evaluated sustainable product-design performance with an *industrial design module* and a *bio-design module* in automobile manufacturers. In this research, both centralized and decentralized models were discussed to analyze the simultaneous, proactive, and reactive approaches.

Even there have been many researches proposed the models to deal with the supply chain, there are only a few studies that applied solely DEA methodology. Almost of study applied DEA as the one part on research such as Lacouture [17] adapted DEA to optimizing B2B transactions in the purchase of construction materials, similarly as Ross [82] who used DEA in benchmarking framework illustrated in the context of a large supply chain system, as same as Lim [64] who proposed an effective benchmarking-path-selection method by using DEA as well.

The analytic hierarchy process (AHP) is a systematic way for subjective decision processes, sensitivity analysis, information about the evaluation criteria implicit weights, better understanding, participation among the members of the decision making groups,and hence, a commitment to the chosen alternative [86]. Lin [65] applied AHP for qualitative performance data. And Lozano [67] utilized AHP to compute relative priorities of inputs and outputs changes before applying DEA. In 2007, Korpelar [56] combined DEA with AHP in selecting the warehouse operator network. In this study, DEA used the preference priorities derived from AHP results as input. These priorities were combined with cost information in order to define the most service/cost-effective warehouse operators.

Besides, dealing with model structure, the data that was used in model is also included. There are many researches that utilize fuzzy measure theory. Fuzzy is one of the famous methods that has been applied with DEA to deal with uncertain data in decision-making process to be more adaptive to the real world [5, 6, 52, 83]. Moreover, there are some researches which have been applied fuzzy logic. For example,

- In the application of performance evaluation for Airport Construction Energy-saving based which convert dimensionless fuzzy number. Then, with the converted fuzzy number as the basis, incomplete weight information as constraint in DEA [97].

- In banking sector, a fuzzy correlation coefficient method has been proposed an using expected value approach which calculates the expected interval and expected value of fuzzy correlation coefficient between fuzzy inputs and fuzzy outputs that were used in DEA model [81].

Rough set theory was also utilized with DEA on supply chain performance evaluation to deal with the difficulty of collecting data by characterizing this rough uncertainty [98]. And Cross-efficiency was applied to solve problem about combinations of information sharing affect the performance and undesirable measures in a supply chain [71]. To consider undesirable outputs, Li [61] proposed model construction method for resource allocation considering undesirable outputs between different decision-making units based on the DEA framework under the CRS and VRS assumption. As well as Shiraz [87] introduced fuzzy rough data envelopment analysis (FRDEA) which apparently provide a way to accommodate the uncertainty.

Due to the fact that traditional DEA models normally assume or require all the data are known precisely. However, in many states, the data are not deterministic. The simulation was introduced to handle with this condition. Additionally, in DEA method, there are some researches that brought up this topic, namely Kuah [58] has carried out DEA method with Monte Carlo simulation to evaluate Knowledge Management performance in higher educational institutions. Wu [96] employed Monte Carlo simulation to investigate and illustrate the performance of the candidate vendors in vendor selection with specific probability distribution in risk-embedded attributes.

Furthermore, there are plenty of methods which were employed with DEA, for instance, balanced scorecard approach [9], data mining [3] and Principal Component Analysis [10].

Besides several of applications on DEA above, there are some researches that reviewed on the different theme which concerned SCM such as environmental efficiency evaluation [88], green supply chain management [72] and fuzzy data envelopment analysis literature [51]. To conclude the applications of DEA in SC performance research, the literature are summarized in Table 2.1.

Table 2.1 – Summary of literature review

Authors	Finding	
	Model	Applications
Seiford Lawrence M. and Zhu Joe [85]	Multi-stages DEA measure the overall efficiency	Commercial banks
Zhu Joe [102]	Multi-stages DEA measure the overall efficiency and its members	
Liang Liang et al. [63]	A two-stages DEA apply game theory for Buyer-Seller situation	
Chen Yao et al. [30]	Examined relations and equivalence between models of Zhu and Liang two models above	Banking industry
Li Hong et al. [61]	Extended Chen's model for addition inputs	China's regions
Zha Yong et al. [100]	Two-stage BCC DEA model by using a geometric-mean method	
Chen Chein-Ming [29]	Network DEA which focus on a dynamic production network	
Farhad Hosseinzadeh Lotfi et al. [66]	Single-stage DEA which deal with total weights flexibility	
Wade D. Cook et al. [36]	Network DEA by considering Stackelberg (leader-follower) and cooperative game concepts	
Chong Wu and David Barnes [95]	Traditional DEA for partner selection and decision making	Agile supply chains
Ci Chen et al. [27]	A two-stages DEA model which considers internal structure under the concepts of (1) centralized, (2) decentralized and (3) mixed.	
Feng Yan et at. [99]	Network DEA concerns internal structure which all members are separated	Banking industry
Mirhedayatian Seyed Mostafa et al. [72]	Multi-stages DEA for green SC	Iranian companies producing soft drinks

Adel Hatami-Marbini et al. [51]	Traditional DEA with fuzzy theorem	
Zhu Zengyin et al. [103]	Network DEA	China's pesticides
Ali Ebrahimnejad et al. [40]	A three-stages DEA	Banking industry
Chin-wei Huang et al. [53]	Modified two-stage DEA model	Taiwanese international hotels
Gokhan Egilmez et al. [41]	Traditional DEA	U.S. food manufacturing sectors
Peter Wanke and Carlos Barrosb [93]	A two-stages DEA	Brazilian banks
Chen Yuh-Jen [32]	Traditional DEA in one of supplier selection steps for SC	Taiwanese textile industry
Haritha Saranga and Roger Moser [84]	Traditional DEA to evaluate the performance of purchasing	Many types of industry
Chen Chialin [27]	A two-stage DEA	Vehicles industry
Castro-Lacouture et al. [17]	Traditional DEA	B2B construction marketplaces
Anthony Ross and Cornelia Droge [82]	Traditional DEA	Distribution centers (DCs) for large supply chain
Lim Sungmook et al.[64]	Traditional DEA	ASIAN container terminals
Shang, Jen S. [86]	Traditional DEA with AHP	Facility layout problem
Lin Ming-Ian Lin [65]	Traditional DEA with AHP	Local government in China
Korpela Jukka et al. [56]	Traditional DEA with AHP	warehouse operators for SC
Xu Jiuping et al. [98]	Traditional DEA with Rough set	Furniture manufacturers in the western region of China

Mentzer John T. et al. [71]	Traditional DEA with Rough set consider undesirable outputs	
Li Hong et al. [61]	Traditional DEA considering undesirable outputs	Resource allocation in China's region
Shiraz Rashed Khanjani et al. [87]	Traditional DEA with fuzzy rough set	
Asosheh Abbas et al. [9]	Traditional DEA with BSC	Iran industry
Akcay Alp Eren [3]	Traditional DEA with data mining	
Song Malin et al. [88]	Traditional DEA	Environment problems

2.5 Conclusion

This review has outlined key areas of literature that may enhance an understanding of views regarding SCM and its performance, DEA and its application on SCM. From the above literature, it is obvious that DEA is brought up in many fields of researches. Conversely, only a few has focused on internal structures and relationship between each member which are a main principle of SCM. For example, agricultural products supply chain, the contract system is applied to connect supplier and manufacture other than products flow. The contract system is introduced into some supply chains to avoid risk resulted from unstable production cost and investment. Regarding to these benefits, some members in SC apply contract system with their suppliers. For the situation of supply chain in which some members are connected, due to their contracts and some are not, the previous models cannot be used. From such reasons, the research's gaps have been identified. The major research gaps come from the consideration of the contract system for suppliers, or no such a contract. Therefore, to fulfill these gaps, this study is intended to provide a more suitable framework to measure the efficiency of a supply chain by developing DEA technique to consider internal structure such as contract relationship between suppliers and manufacture. The proposed methodology comprises an alternative DEA model which integrates two types of contracted supplier and non-contracted supplier that are irreplaceable and replaceable, respectively. The proposed models will enable organizations to improve supply chain efficiency in the case that efficiency of non-contracted suppliers is measured. The research outline is discussed in the next chapter.

3 Outline of the research

3.1 Introduction

The chapter reviews a research outline of this study. It begins with a procedure of this study then followed along with details of each specific research phase, and lastly limitations of this research. This research utilized studied supply chains in Thai frozen food industry sector to realize that the research aim is to show applicability of the proposed method in the next two chapters (Chapter Five) using the proposed models which have been developed in the following chapter (Chapter Four). There are also discussions of an approach for applying the proposed models to a case study in the last phase in the last chapter (Chapter Six).

The research procedure in this study consists of five phases. Firstly, background and related literature, which are reviewed to examine gaps within the research interest area. Secondly, an alternative method to evaluate efficiency of supply chain is proposed. To show the efficiency of proposed method, a case-study approach is utilized. In this phase, a sample group in case study is chosen, and all related data is gathered. In the fourth phase, as a result of the previous phase, the case study is evaluated efficiency by using the proposed method. Finally, discussions and conclusions are demonstrated.

3.2 Define statement problem, scope and literature review

At first, at an initial stage of the research, problems had been identified from preliminary review of literature. This process had involved stages of revision of the original ideas until gaps were identified within the area of research interests. The literature was thoroughly analyzed in order to determine whether those questions had been answered [78]. The research aim was then identified based on research questions, and the research objectives were derived from the main aim, being refined several times in the process. Then, to approach the research aim, literature was further studied to establish an appropriate theory. Key concepts or variables involved in the subject of research were identified. The reviewed literature covers several areas, supply chain management, evaluation of supply chain performance and data envelopment analysis. Finally, the application of data envelopment analysis on the measurement to supply chain performance was focused on.

3.3 Design and develop efficiency evaluation model

The proposed models which are constructed in this step are used to describe a supply chain considers different contract types of suppliers, contracted and non-contracted suppliers. The contracted supplier cannot be replaced because of its agreement with manufacturer but the non-contracted can be replaced. To evaluate efficiency of supply chain precisely, supply chain structure should be concerned. Since a principle of SCM is to archive its goal by the members' cooperation, the contract relationship between members is dramatically critical. In this research, I focus on multiple suppliers in supply chain, and a relationship between the supplier and the manufacturer is also taken into an account. Evaluation models are then designed and developed based on a DEA technique. In design and develop model process, concepts of DEA and its applications are investigated, and then the proposed models are structured. After defining the proposed model for multiple suppliers supply chain, the proposed models are compare compare with the conventional models by applying mathematical proof.

3.4 Find the factors and collect data that related to factors

A case-study approach can be used to show the applicability of models, frameworks, or theories, which can then be extended to other cases in similar situations [78]. To establish the applicability of the proposed models, thus, a case-study approach is applied. By considering the relationship of suppliers in supply chain, the case-study supply chain structure can represent a supply chain which different types of suppliers are involved. The major aim of this research is to develop efficiency evaluation models based on potential structure and to apply these proposed models in actual supply chain contexts. In this study, the proposed models are used to measure efficiency of frozen food supply chains in Thailand. In literature study, performance criteria which are chosen on this step are considered as the primary criteria of framework. Then the expert's interview was presented to ensure appropriateness of the criteria. The questionnaire-and-interviews approach is applied with sample groups to gather the efficiency data. The selection of the case studies was also influenced by consideration of the practical feasibility of access to the case study sample group [78]. Due to this concern, the author chose Thailand as it is my country of origin. With this, it provides me the convenience of collecting data in my native language. In addition regarding my background experiences and studies, I had network of contacts that helped to gain access to key informants in the case-study supply chains. And case studies can be particularly valuable because the data which has been utilized represent their performance based on their supply chain structure precisely.

3.5 Case study to evaluate the proposed method

In this research, Thai frozen food industry is chosen as an example. After getting all data for measurement, the proposed models are applied to measure an efficiency of the supply chains. The result of the proposed models are analyzed to identify the efficiency of each chain based on supply chain structure.

3.6 Research discussion and conclusion

There are conclusions of the proposed models for supply chain efficiency evaluation considers replaceable suppliers. The application of the proposed models on Thai frozen food industry is also discussed and directions for future works are also mentioned in this phase.

3.7 Research Limitations

The proposed models are constructed based on supplier-manufacturer structure. In the proposed models, replaceable suppliers are allowed to compare with others. To apply efficient replaceable suppliers, I assumed that their inputs decrease while their outputs (intermediate products) remain the same level. Regarding to this, it avoids a change of intermediate products which affect to manufacturers' side. But generally supply chain consists more than suppliers and manufacturers, for example, transporters, retailers and so on. Consequently, this proposed method can't be use directly.

The research followed a well-prepared process based on a carefully developed research design. Despite this, there were three main limitations that had effects to this study. Firstly, there were limited resources for the research due to the case studies that are undertaken in Thailand which caused difficulties in gathering efficiency data. Secondly, some organizations in the case studies had not gathered the data were to be used in the proposed models. Since that, some efficiency data is only the estimation from informants. Finally, in gathering efficiency data, some organizations are prohibited to give out their inner data to outsiders. However, the researcher has been finding some spare organizations to confirm the amount of case studies is enough for measurement.

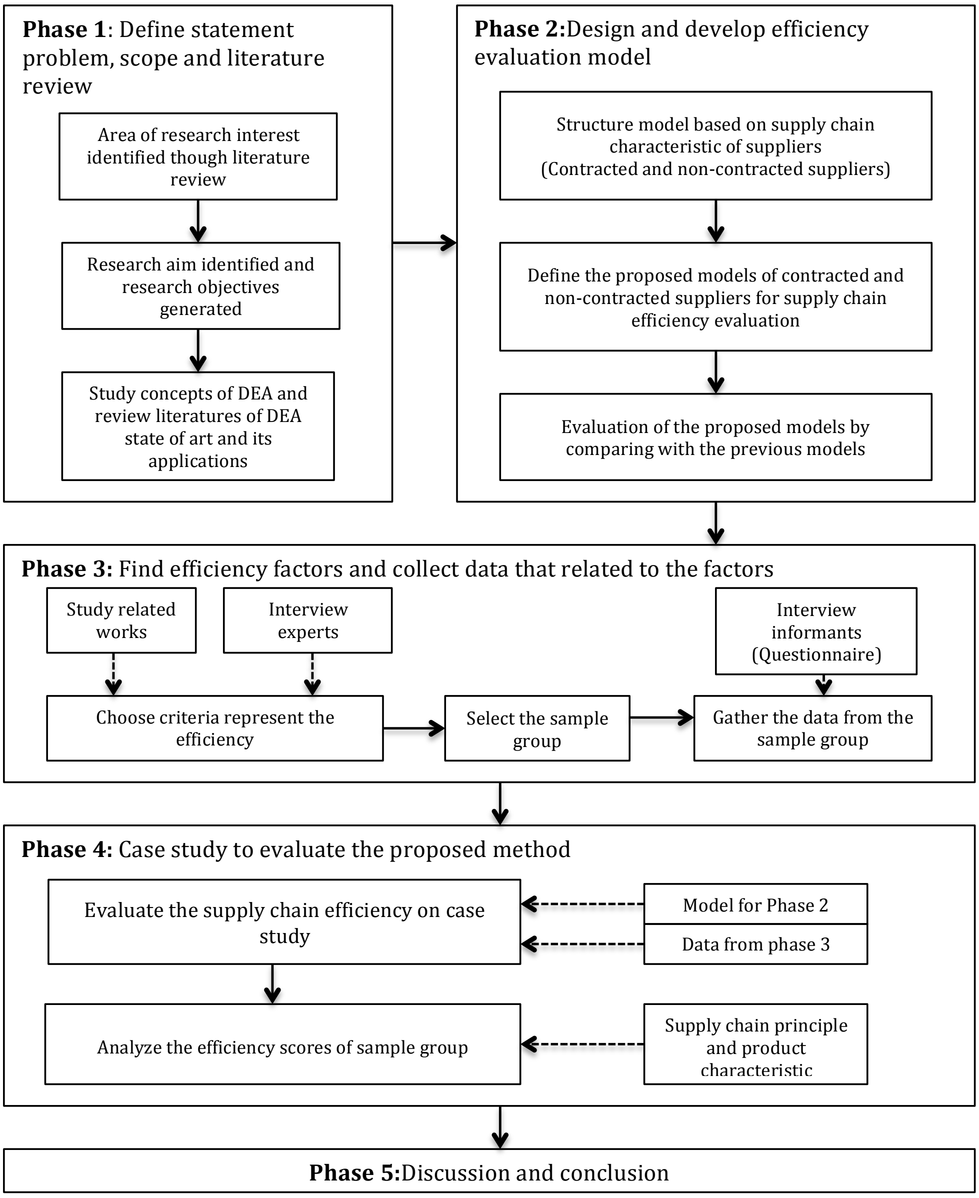


Figure 3.1 – Research Process

3.8 Conclusion

This chapter has presented the outline which has guided the research designs, methodology, and methods. The overview of the methodology is explained as shown in Fig. 3.1.

After the research questions are designed, the design and develop model was considered an appropriateness in order to measure efficiency of supply chain based on DEA approach. The propriety of the proposed method was validated by mathematical proof. This study adopts a case-study approach to allow the method to show the applicability of the proposed method. The efficiency results were analyzed based on the principle of supply chain. There are also discussions about the applicability, contributions, and some limitations of this research.

The following chapter identifies the development of conceptual framework that has been used in this research. The proposed framework has the intention to explain the conceptual logic and direction of this study.

4 Efficiency Evaluation Model

4.1 Introduction

Alternative models to evaluate efficiency of supply chain are described in this chapter. A concept of contract relationship between supplier and manufacturer are considered in these alternative models. In multiples suppliers supply chain, two types of them is considered as non-contracted one which is replaceable and contracted one which irreplaceable. A two-stage network DEA is extended to include such types of suppliers. The supply chain in which all suppliers are irreplaceable, a conventional DEA can be utilized. Whereas the supply chain in which some supplier can be replaced, it may not suitable. In the following, I first present an extended model of all supplier is replaceable and a model for some suppliers are replaceable, and the modeling rationale of the models in details.

4.2 The model for supply chain

For the simplicity, a two stage supplier-manufacture chain is consider as following in Fig. 5.4, where $S1, S2$ and M represent the supplier 1, the supplier 2, and the manufacturer, respectively. X^1 and X^2 stand for inputs of supplier 1 ($S1$) and supplier 2 ($S2$) respectively. Intermediate products of $S1$ and $S2$ are Y^1 and Y^2 accordingly. And final output is Z.

A structure which is use in this research is shown in fig. 4.1. This structure represents a supply chain which includes multiple suppliers. X^1 and X^2 stand for inputs of supplier 1 ($S1$) and supplier 2 ($S2$) respectively. Intermediate products of $S1$ and $S2$ are Y^1 and Y^2 accordingly. And final output is Z.

Let

$\theta_{(o)}$: Efficiency score of in-considering DMU.

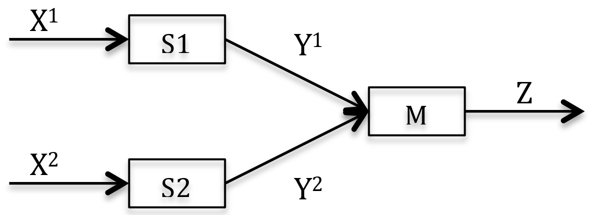


Figure 4.1 – Structure of chain

$\theta_{s1(o)}$: Efficiency score of supplier 1 for in-considering DMU ($1 \le o \le j$).

$\theta_{s2(o)}$: Efficiency score of supplier 2 for in-considering DMU ($1 \le o \le j$).

$\theta_{m(o)}$: Efficiency score of manufacturer for in-considering DMU ($1 \le o \le j$).

$X^1_{(ij)}$: Vector of i-th inputs for supplier 1's in j-th DMU.

$X^1_{(io)}$: Vector of i-th inputs for supplier 1's for in-considering DMU ($1 \le o \le j$).

$Y^1_{(lj)}$: Vector of l-th intermediate products of supplier 1 in j-th DMU.

$Y^1_{(lo)}$: Vector of l-th intermediate products of supplier 1 for in-considering DMU ($1 \le o \le j$).

$X^2_{(ij)}$: Vector of i-th supplier 2's inputs in j-th DMU.

$X^2_{(io)}$: Vector of i-th supplier 2's inputs for in-considering DMU ($1 \le o \le j$).

$Y^2_{(lj)}$: Vector of l-th intermediate products of supplier 2 in j-th DMU.

$Y^2_{(lo)}$: Vector of l-th intermediate products of supplier 2 for in-considering DMU ($1 \le o \le j$).

$Z_{(kj)}$: Vector of k-th final outputs for manufacturer of j-th DMU.

$Z_{(ko)}$: Vector of k-th final outputs for manufacturer for in-considering DMU ($1 \le o \le j$).

n : The number of DMUs.

I : The number of supplier's inputs.

L : The number of intermediate products.

K : The number of final outputs.

An efficiency of S1, S2, and M can be calculated by following model, respectively.

$$(s1)\left|\begin{array}{ll} \text{minimize} & \theta_{s1(o)} \\ subject\ to & \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \leq \theta_{s1(o)} X^1_{(io)} \\ & \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \\ & \lambda^1_{(j)} \geq 0 \end{array}\right.$$

$$(s2)\left|\begin{array}{ll} \text{minimize} & \theta_{s2(o)} \\ subject\ to & \sum_{j=1}^{n} \lambda^1_{(j)} X^2_{(ij)} \leq \theta_{s2(o)} X^2_{(io)} \\ & \sum_{j=1}^{n} \lambda^1_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)} \\ & \lambda^2_{(j)} \geq 0 \end{array}\right.$$

$$(m)\left|\begin{array}{ll} \text{minimize} & \theta_{m(o)} \\ subject\ to & \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq \theta_{m(o)} Y^1_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq \theta_{m(o)} Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)} \\ & \lambda^2_{(j)} \geq 0 \end{array}\right.$$

The traditional DEA which considers all process as black box is shown in following model.

$$(Traditional)\left|\begin{array}{ll} \text{minimize} & \theta_{T(o)} \\ subject\ to & \theta_{T(o)} X^1_{(io)} - \sum_{j=1}^{n} \lambda_{(j)} X^1_{(ij)} \geq 0 \\ & \theta_{T(o)} X^2_{(io)} - \sum_{j=1}^{n} \lambda_{(j)} X^2_{(ij)} \geq 0 \\ & \sum_{j=1}^{n} \lambda_{(j)} Z_{(kj)} \geq Z_{(ko)} \\ & \lambda_{(j)} \geq 0 \end{array}\right.$$

The network DEA which is introduced by Chen and Yan in 2011 [26] is considered as network DEA for supply chain. The production possibility set of their model according to this structure is present as follows:

$$T_{Network} = \{((X^1_{(io)}, X^2_{(io)}, Y^1_{(lo)}, Y^2_{(lo)}, Z_{(ko)}) | \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \le X^1_{(io)}, \quad \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \ge Y^1_{(lo)},$$
$$\sum_{j=1}^{n} \lambda^2_{(j)} X^2_{(ij)} \le X^2_{(io)}, \quad \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \ge Y^2_{(lo)},$$
$$\sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \le Y^1_{(lo)}, \quad \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \le Y^2_{(lo)},$$
$$\sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \ge Z_{(ko)}, \quad \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \le 0\}$$

Accordingly, its DEA model is expressed as,

$$(Network) \quad \left| \begin{array}{ll} \text{minimize} & \theta_{Network(o)} \\ subject\ to & \theta_{Network(o)} X^1_{(io)} - \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \ge 0 \\ & \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \ge Y^1_{(lo)} \\ & \theta_{Network(o)} X^2_{(io)} - \sum_{j=1}^{n} \lambda^2_{(j)} X^2_{(ij)} \ge 0 \\ & \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \ge Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \le Y^1_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \le Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \ge Z_{(ko)} \\ & \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \ge 0 \end{array} \right.$$

By using this model, each member is chain is not allowed to be compare efficiency with others.In year 2009, Yang et.al. [99] introduced the supply chain DEA model under consumption that each member in a chain can be replaced by applying each member efficiency score first. But is a supply chain in which there are many suppliers, the contact of supply is considered. Some supply chain, all supplier can be changed but in some supply chain in which some suppliers are connected by agreement and some are not, for example in food industry which farmers and factories are connected by agreement. Therefore situation of suppliers is difference. Members in the chain are not only link by amount of intermediate product, and some members cannot be separated freely.

4.3 Models

Several models that can directly evaluate the performance of supply chain while considering the above mentioned situation are developed. The modeling processes are analyzed based upon the concept of replaceable and irreplaceable suppliers. The models will be proposed by extending the model of Yang [99]. The model $(Network)$ stands for the conventional network DEA model which is not allows suppliers to replace by others suppliers. The model (all) represents the network DEA model which every supplier in chain can be replaced by others and the model $(some)$ denotes the network DEA model for supply chain which some suppliers can be replaced but some does not.

The proposed models are discussed under the following two conditions:

Condition 1 :
All supply chain members are described by CRS (constant returns to scare) or CCR model, which means if the inputs increase, the outputs will increase in same proportion;

Condition 2 :
The suppliers which can be separated can be recombined into other supply chain without extra cost.

Under CRS condition, each supplier has a unique input-oriented projection in a production frontier by proportionally reduce inputs X_j while remains outputs Y_j unchanged.

4.3.1 All supplier can be replaced

In some supply chain which all supplier can be changed or replaceable, it means a manufacturer is allowed to compare an efficiency of all suppliers with all existing suppliers. The structure of this chain is shown as Fig. 4.2.

The production possibility set of the proposed model is,

$$T_{all} = \{(X^1_{(io)}, X^2_{(io)}, Y^1_{(lo)}, Y^2_{(lo)}, Z_{(ko)}) | \sum_{j=1}^{n} \lambda^1_{(j)} \theta_{s1(o)} X^1_{(ij)} \leq X^1_{(io)}, \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)},$$

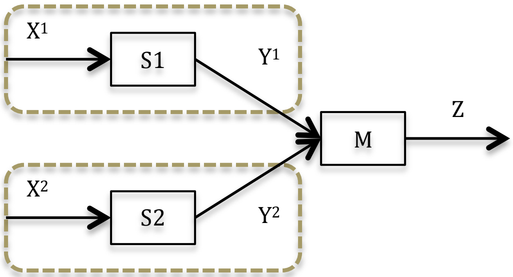


Figure 4.2 – Structure of chain which all supplier is replaceable

$$\sum_{j=1}^{n} \lambda^2_{(j)}\theta_{s2(o)}X^2_{(ij)} \le X^2_{(io)}, \sum_{j=1}^{n} \lambda^2_{(j)}Y^2_{(lj)} \ge Y^2_{(lo)},$$
$$\sum_{j=1}^{n} \lambda^3_{(j)}Y^1_{(lj)} \le Y^1_{(lo)}, \sum_{j=1}^{n} \lambda^3_{(j)}Y^2_{(lj)} \le Y^2_{(lo)},$$
$$\sum_{j=1}^{n} \lambda^3_{(j)}Z_{(kj)} \ge Z_{(ko)}, \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \ge 0\}$$

where $\theta_{s1(o)}, \theta_{s2(o)}$ is an efficiency score of replaceable supplier which is calculated by model $(s1)$ and $(s2)$.

The efficiency of chain can be computed using model:

$$(all) \left| \begin{array}{ll} \text{minimize} & \theta_{all(o)} \\ subject\ to & \theta_{all(o)}X^1_{(io)} - \sum_{j=1}^{n} \lambda^1_{(j)}\theta_{s1(o)}X^1_{(ij)} \ge 0 \\ & \sum_{j=1}^{n} \lambda^1_{(j)}Y^1_{(lj)} \ge Y^1_{(lo)} \\ & \theta_{all(o)}X^2_{(io)} - \sum_{j=1}^{n} \lambda^2_{(j)}\theta_{s2(o)}X^2_{(ij)} \ge 0 \\ & \sum_{j=1}^{n} \lambda^2_{(j)}Y^2_{(lj)} \ge Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)}Y^1_{(lj)} \le Y^1_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)}Y^2_{(lj)} \le Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)}Z_{(kj)} \ge Z_{(ko)} \\ & \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \ge 0 \end{array} \right.$$

4.3.2 Some suppliers are replaceable

In this type of supply chain, some suppliers are connected by agreement and some are not, for example in food industry which farmers and factories are connected by agreement. That means a manufacture is only allowed to compare replaceable suppliers efficiency. The structure of this kind of supply chain is show in Fig. 4.3

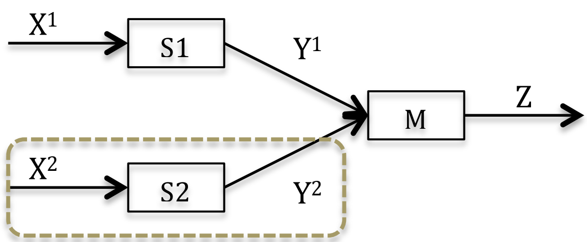


Figure 4.3 – Structure of chain which some suppliers are replaceable

$S2$ represents a supplier which can be changed or replaced. The production possibility set of the proposed model is,

$$\begin{aligned} T_{some} = \{((X^1_{(io)}, X^2_{(io)}, Y^1_{(lo)}, Y^2_{(lo)}, Z_{(ko)}) | \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \leq X^1_{(io)}, \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)}, \\ \sum_{j=1}^{n} \lambda^2_{(j)} \theta_{s2(o)} X^2_{(ij)} \leq X^2_{(io)}, \ \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)}, \\ \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)}, \ \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)}, \\ \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)}, \ \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \geq 0\} \end{aligned}$$

where $\theta_{s2(o)}$ is an efficiency score of replaceable supplier which is calculated by model $(s2)$. The efficiency of chain can be computed using model:

$$
(some)\quad
\begin{array}{|ll}
\text{minimize} & \theta_{some(o)} \\
subject\ to & \theta_{some(o)} X^1_{(io)} - \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \geq 0 \\
& \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \\
& \theta_{some(o)} X^2_{(io)} - \sum_{j=1}^{n} \lambda^2_{(j)} \theta_{s2(o)} X^2_{(ij)} \geq 0 \\
& \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)} \\
& \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \geq 0
\end{array}
$$

Efficiency analysis

Efficiency on supply chain from the following three aspect is discussed:

(I) supply chain efficiency and member efficiency;

(II) supply chain efficiency in three different structure;

(III) supply chain efficiency and CCR efficiency.

4.3.3 Supply chain efficiency and member efficiency

Let $\theta^*_{Network(o)}, \theta^*_{s1(o)}, \theta^*_{s2(o)}, \theta^*_{m(o)}$ be the optimal values corresponding to model $(Network), (s1), (s2)$ and (m), respectively.

Proposition 1 In the network structure supply chain, the supply chain efficiency and each member have the following relationship.

$\theta^*_{Network(o)} \leq \theta^*_{s1(o)} * \theta^*_{s2(o)} * \theta^*_{m(o)}$

Proof. Denote $\theta^*_{s1(o)}, \lambda^{1*}_{(j)}; \theta^*_{s2(o)}, \lambda^{2*}_{(j)}; \theta^*_{m(o)}, \lambda^{3*}_{(j)}, j = 1, \ldots, n$ as the optimal pair of solutions corresponding to model $(s1),(s2)$ and (m), respectively. And let $P1$ is :

$$\sum_{j=1}^{n}\lambda_{(j)}^{1*}X_{(ij)}^{1}\leq\theta_{s1(o)}^{*}X_{(io)}^{1} \tag{4.1a}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{1*}Y_{(lj)}^{1}\geq Y_{(lo)}^{1} \tag{4.1b}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{2*}X_{(ij)}^{2}\leq\theta_{s2(o)}^{*}X_{(io)}^{2} \tag{4.1c}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{2*}Y_{(lj)}^{2}\geq Y_{(lo)}^{2} \tag{4.1d}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{3*}Y_{(lj)}^{1}\leq\theta_{m(o)}^{*}Y_{(lo)}^{1} \tag{4.1e}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{3*}Y_{(lj)}^{2}\leq\theta_{m(o)}^{*}Y_{(lo)}^{2} \tag{4.1f}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{3*}Z_{(kj)}\geq Z_{(ko)} \tag{4.1g}$$

(4.1a) and (4.1b) are taken from model $(s1)$. (4.1c) and (4.1d) are taken from model $(s2)$. (4.1e), (4.1f) and (4.1g) are taken from model (m). First, I prove that the feasible region of model $(Network)$ is greater than $(P1)$. By divide $\theta_{s1(o)}^{*}$ on both side of (4.1a), (4.1b) and let $\lambda^{1*'}=\frac{\lambda^{1*}}{\theta_{s1(o)}^{*}}$, divide $\theta_{s2(o)}^{*}$ on both side of (4.1c), (4.1d) and let $\lambda^{2*'}=\frac{\lambda^{2*}}{\theta_{s2(o)}^{*}}$, $\theta_{m(o)}^{*}$ on both side of (4.1e), (4.1f), (4.1g) and let $\lambda^{3*'}=\frac{\lambda^{3*}}{\theta_{m(o)}^{*}}$ (To set (4.1a), (4.1c), (4.1e) and (4.1f) in same structure in model $(Network)$ and compare only (4.1b), (4.1d) and (4.1g)). Then let $P1$ is:

$$\sum_{j=1}^{n}\lambda_{(j)}^{1*'}X_{(ij)}^{1}\leq X_{(io)}^{1} \tag{4.2a}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{1*'}Y_{(lj)}^{1}\geq\frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \tag{4.2b}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{2*'}X_{(ij)}^{2}\leq X_{(io)}^{2} \tag{4.2c}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{2*'}Y_{(lj)}^{2}\geq\frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \tag{4.2d}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{3*'}Y_{(lj)}^{1}\leq Y_{(lo)}^{1} \tag{4.2e}$$

$$\sum_{j=1}^{n}\lambda_{(j)}^{3*'}Y_{(lj)}^{2}\leq Y_{(lo)}^{2} \tag{4.2f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \geq \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \tag{4.2g}$$

Then, $P1$ with feasible region of model $(Network)$ is compared by merge them together and $0 < \theta_{s1(o)}^{*}, \theta_{s2(o)}^{*}, \theta_{m(o)}^{*} \leq 1$, then we get:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} X_{(ij)}^{1} \leq X_{(io)}^{1} \tag{4.3a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \geq \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \geq Y_{(lo)}^{1} \tag{4.3b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} X_{(ij)}^{2} \leq X_{(io)}^{2} \tag{4.3c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \geq \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \geq Y_{(lo)}^{2} \tag{4.3d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.3e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.3f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \geq \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \geq Z_{(ko)} \tag{4.3g}$$

The connect the above facts, we see that the feasible region of $(Network)$ is greater than $(P1)$. Thus, $\theta_{Network(o)}^{*} \leq \theta_{s1(o)}^{*} * \theta_{s2(o)}^{*} * \theta_{m(o)}^{*}$. □

Proposition 2 In the same way, we prove that

$\theta_{some(o)}^{*} \leq \theta_{s1} * \theta_{s2} * \theta_{m}$.

Proof. Denote $\theta_{s1(o)}^{*}, \lambda_{(j)}^{1*}; \theta_{s2(o)}^{*}, \lambda_{(j)}^{2*}; \theta_{m(o)}^{*}, \lambda_{(j)}^{3*}, j = 1, \ldots, n$ as the optimal pair of solutions corresponding to model $(s1), (s2)$ and (m), respectively. And let $P1$ is :

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*} X_{(ij)}^{1} \leq \theta_{s1(o)}^{*} X_{(io)}^{1} \tag{4.4a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*} Y_{(lj)}^{1} \geq Y_{(lo)}^{1} \tag{4.4b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} X_{(ij)}^{2} \leq \theta_{s2(o)}^{*} X_{(io)}^{2} \tag{4.4c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} Y_{(lj)}^{2} \geq Y_{(lo)}^{2} \tag{4.4d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{1} \leq \theta_{m(o)}^{*} Y_{(lo)}^{1} \tag{4.4e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{2} \leq \theta_{m(o)}^{*} Y_{(lo)}^{2} \tag{4.4f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Z_{(kj)} \geq Z_{(ko)} \tag{4.4g}$$

(4.4a) and (4.4b) are taken from model $(s1)$. (4.4c) and (4.4d) are taken from model $(s2)$. (4.4e), (4.4f) and (4.4g) are taken from model (m). First, I prove that the feasible region of model $(some)$ is greater than $(P1)$. By divide $\theta_{s1(o)}^{*}$ on both side of (4.4a), (4.4b) and let $\lambda^{1*'} = \frac{\lambda^{1*}}{\theta_{s1(o)}^{*}}$, divide $\theta_{s2(o)}^{*}$ on both side of (4.4c), (4.4d) and let $\lambda^{2*'} = \frac{\lambda^{2*}}{\theta_{s2(o)}^{*}}$, $\theta_{m(o)}^{*}$ on both side of (4.4e), (4.4f), (4.4g) and let $\lambda^{3*'} = \frac{\lambda^{3*}}{\theta_{m(o)}^{*}}$ (To set (4.4a), (4.4e) and (4.4f) in same structure in model $(some)$ and compare only (4.4b), (4.4c), (4.4d) and (4.4g)). Then $P1$ is:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} X_{(ij)}^{1} \leq X_{(io)}^{1} \tag{4.5a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \geq \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \tag{4.5b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} X_{(ij)}^{2} \leq X_{(io)}^{2} \tag{4.5c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \geq \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \tag{4.5d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.5e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.5f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \geq \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \tag{4.5g}$$

Now θ_{s2} is multiplied to (4.5c) to transform it as same structure in model $(some)$, then it is obtained that:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} X_{(ij)}^{1} \leq X_{(io)}^{1} \tag{4.6a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \geq \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \tag{4.6b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} \theta_{s2(o)} X_{(ij)}^{2} \leq \theta_{s2(o)} X_{(io)}^{2} \tag{4.6c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \geq \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \tag{4.6d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \le Y_{(lo)}^{1} \tag{4.6e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \le Y_{(lo)}^{2} \tag{4.6f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \ge \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \tag{4.6g}$$

To compare with the feasible region of $(some)$, it is obtained that:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} X_{(ij)}^{1} \le X_{(io)}^{1} \tag{4.7a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \ge \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \ge Y_{(lo)}^{1} \tag{4.7b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} \theta_{s2(o)} X_{(ij)}^{2} \le \theta_{s2(o)} X_{(io)}^{2} \le X_{(io)}^{2} \tag{4.7c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \ge \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \ge Y_{(lo)}^{2} \tag{4.7d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \le Y_{(lo)}^{1} \tag{4.7e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \le Y_{(lo)}^{2} \tag{4.7f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \ge \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \ge Z_{(ko)} \tag{4.7g}$$

The connect the above facts, we see that the feasible region of $(some)$ is greater than $(P1)$. Thus, $\theta_{some(o)}^{*} \le \theta_{s1(o)}^{*} * \theta_{s2(o)}^{*} * \theta_{m(o)}^{*}$. □

Proposition 3 In the same way, we prove that

$\theta_{all(o)}^{*} \le \theta_{s1} * \theta_{s2} * \theta_{m}$.

Proof. Denote $\theta_{s1(o)}^{*}, \lambda_{(j)}^{1*}; \theta_{s2(o)}^{*}, \lambda_{(j)}^{2*}; \theta_{m(o)}^{*}, \lambda_{(j)}^{3*}, j = 1, \ldots, n$ as the optimal pair of solutions corresponding to model $(s1), (s2)$ and (m), respectively. And let $P1$ is :

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*} X_{(ij)}^{1} \le \theta_{s1(o)}^{*} X_{(io)}^{1} \tag{4.8a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*} Y_{(lj)}^{1} \ge Y_{(lo)}^{1} \tag{4.8b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} X_{(ij)}^{2} \le \theta_{s2(o)}^{*} X_{(io)}^{2} \tag{4.8c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} Y_{(lj)}^{2} \ge Y_{(lo)}^{2} \tag{4.8d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{1} \leq \theta_{m(o)}^{*} Y_{(lo)}^{1} \tag{4.8e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{2} \leq \theta_{m(o)}^{*} Y_{(lo)}^{2} \tag{4.8f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Z_{(kj)} \geq Z_{(ko)} \tag{4.8g}$$

(4.8a) and (4.8b) are taken from model $(s1)$. (4.8c) and (4.8d) are taken from model $(s2)$. (4.8e), (4.8f) and (4.8g) are taken from model (m). First, I prove that the feasible region of model (all) is greater than $(P1)$. By divide $\theta_{s1(o)}^{*}$ on both side of (4.8a), (4.8b) and let $\lambda^{1*'} = \frac{\lambda^{1*}}{\theta_{s1(o)}^{*}}$, divide $\theta_{s2(o)}^{*}$ on both side of (4.8c), (4.8d) and let $\lambda^{2*'} = \frac{\lambda^{2*}}{\theta_{s2(o)}^{*}}$, $\theta_{m(o)}^{*}$ on both side of (4.8e), (4.8f), (4.8g) and let $\lambda^{3*'} = \frac{\lambda^{3*}}{\theta_{m(o)}^{*}}$ (To set (4.8e) and (4.8f) in same structure in model $(some)$ and compare only (4.8a), (4.8b), (4.8c), (4.8d) and (4.8g)). Then $P1$ is:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} X_{(ij)}^{1} \leq X_{(io)}^{1} \tag{4.9a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \geq \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \tag{4.9b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} X_{(ij)}^{2} \leq X_{(io)}^{2} \tag{4.9c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \geq \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \tag{4.9d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.9e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.9f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \geq \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \tag{4.9g}$$

Then, multiply θ_{s1} to (4.9a) θ_{s2} to (4.9c) to transform it as same structure in model (all), we can see that:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} \theta_{s1(o)} X_{(ij)}^{1} \leq \theta_{s1} X_{(io)}^{2} \tag{4.10a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \geq \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \tag{4.10b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} \theta_{s2(o)} X_{(ij)}^{2} \leq \theta_{s2} X_{(io)}^{2} \tag{4.10c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \geq \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \tag{4.10d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.10e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.10f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \geq \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \tag{4.10g}$$

To compare with the feasible region of (all), it is obtained that:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} \theta_{s1(o)} X_{(ij)}^{1} \leq \theta_{s1} X_{(io)}^{1} \leq X_{(io)}^{1} \tag{4.11a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*'} Y_{(lj)}^{1} \geq \frac{Y_{(lo)}^{1}}{\theta_{s1(o)}^{*}} \geq Y_{(lo)}^{1} \tag{4.11b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} \theta_{s2(o)} X_{(ij)}^{2} \leq \theta_{s2} X_{(io)}^{2} \leq X_{(io)}^{2} \tag{4.11c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*'} Y_{(lj)}^{2} \geq \frac{Y_{(lo)}^{2}}{\theta_{s2(o)}^{*}} \geq Y_{(lo)}^{2} \tag{4.11d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.11e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.11f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*'} Z_{(kj)} \geq \frac{Z_{(ko)}}{\theta_{m(o)}^{*}} \geq Z_{(ko)} \tag{4.11g}$$

The connect the above facts, we see that the feasible region of (all) is greater than $(P1)$. Thus, $\theta_{all(o)}^{*} \leq \theta_{s1(o)}^{*} * \theta_{s2(o)}^{*} * \theta_{m(o)}^{*}$. □

4.3.4 Supply chain efficiency in three different structure

Due to the difference between each model, this section shows a relationship among them. Let $\theta_{Network(o)}^{*}, \theta_{all(o)}^{*}, \theta_{some(o)}^{*}$ be the optimal values corresponding to model $(Network), (all)$ and $(some)$, respectively.

Proposition 4 The relationship of supply chain efficiency of each the above mentioned situation can be expressed as:

$\theta_{all(o)}^{*} \leq \theta_{some(o)}^{*} \leq \theta_{Network(o)}^{*}$

First, $\theta_{some(o)}^{*} \leq \theta_{Network(o)}^{*}$ is proved.

Proof. Let $\theta^*_{Network(o)}, \lambda^{1*}_{(j)}, \lambda^{2*}_{(j)}, \lambda^{3*}_{(j)}, j = 1, \ldots, n$ be any optimal of model $(Network)$. That is:

$$\sum_{j=1}^{n} \lambda^{1*}_{(j)} X^1_{(ij)} \leq \theta^*_{Network(o)} X^1_{(io)} \tag{4.12a}$$

$$\sum_{j=1}^{n} \lambda^{1*}_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \tag{4.12b}$$

$$\sum_{j=1}^{n} \lambda^{2*}_{(j)} X^2_{(ij)} \leq \theta^*_{Network(o)} X^2_{(io)} \tag{4.12c}$$

$$\sum_{j=1}^{n} \lambda^{2*}_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)} \tag{4.12d}$$

$$\sum_{j=1}^{n} \lambda^{3*}_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)} \tag{4.12e}$$

$$\sum_{j=1}^{n} \lambda^{3*}_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)} \tag{4.12f}$$

$$\sum_{j=1}^{n} \lambda^{3*}_{(j)} Z_{(kj)} \geq Z_{(ko)} \tag{4.12g}$$

To compare with the feasible region of $(some)$, θ_{s2} is multiplied to (4.12c) and (4.12d) and let

$$\sum_{j=1}^{n} \lambda^{1*}_{(j)} X^1_{(ij)} \leq \theta^*_{Network(o)} X^1_{(io)} \tag{4.13a}$$

$$\sum_{j=1}^{n} \lambda^{1*}_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \tag{4.13b}$$

$$\sum_{j=1}^{n} \bar{\lambda}^{2*}_{(j)} X^2_{(ij)} \leq \theta^*_{Network(o)} \theta_{s2} X^2_{(io)} \tag{4.13c}$$

$$\sum_{j=1}^{n} \bar{\lambda}^{2*}_{(j)} Y^2_{(lj)} \geq \theta_{s2} Y^2_{(lo)} \tag{4.13d}$$

$$\sum_{j=1}^{n} \lambda^{3*}_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)} \tag{4.13e}$$

$$\sum_{j=1}^{n} \lambda^{3*}_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)} \tag{4.13f}$$

$$\sum_{j=1}^{n} \lambda^{3*}_{(j)} Z_{(kj)} \geq Z_{(ko)} \tag{4.13g}$$

(4.13a), (4.13b), (4.13e), (4.13f) and (4.13g) are same as in $(Network)$. Because $0 < \theta_{s2(o)} \leq 1$ from model $(s2)$, comparing (4.13c) and (4.13d) with $(Network)$, that is:

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{2*} X_{(ij)}^{2} \leq \theta_{Network(o)}^{*} \theta_{s2} X_{(io)}^{2} \leq \theta_{Network(o)}^{*} X_{(io)}^{2} \tag{4.14a}$$

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{2*} Y_{(lj)}^{2} \geq Y_{(lo)}^{2} \geq \theta_{s2} Y_{(lo)}^{2} \tag{4.14b}$$

(4.13a)-(4.13d) and (4.14a), (4.14b) imply that the feasible region of $(some)$ is greater than $(Network)$. Thus, $\theta_{some(o)}^{*} \leq \theta_{Network(o)}^{*}$.

□

Second, $\theta_{all(o)} \leq \theta_{some(o)}$ is proved.

Proof. Let $\theta_{some(o)}^{*}, \lambda_{(j)}^{1*}, \lambda_{(j)}^{2*}, \lambda_{(j)}^{3*}, j = 1, \dots, n$ be any optimal of model $(some)$. That is:

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*} X_{(ij)}^{1} \leq \theta_{some(o)}^{*} X_{(io)}^{1} \tag{4.15a}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{1*} Y_{(lj)}^{1} \geq Y_{(lo)}^{1} \tag{4.15b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} \theta_{s2} X_{(ij)}^{2} \leq \theta_{some(o)}^{*} X_{(io)}^{2} \tag{4.15c}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} Y_{(lj)}^{2} \geq Y_{(lo)}^{2} \tag{4.15d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.15e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.15f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Z_{(kj)} \geq Z_{(ko)} \tag{4.15g}$$

To compare with the feasible region of (all), θ_{s1} is multiplied to (15a) and (15b) and let $\bar{\lambda}_{(j)}^{1*} = \theta_{s1(o)}^{*} * \lambda_{(j)}^{1*}$. That is:

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{1*} X_{(ij)}^{1} \leq \theta_{some(o)}^{*} \theta_{s1} X_{(io)}^{1} \tag{4.16a}$$

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{1*} Y_{(lj)}^{1} \geq \theta_{s1} Y_{(lo)}^{1} \tag{4.16b}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{2*} \theta_{s2(o)} X_{(ij)}^{2} \leq \theta_{some(o)}^{*} X_{(io)}^{2} \tag{4.16c}$$

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{2*} Y_{(lj)}^{2} \geq \theta_{s2} Y_{(lo)}^{2} \tag{4.16d}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{1} \leq Y_{(lo)}^{1} \tag{4.16e}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Y_{(lj)}^{2} \leq Y_{(lo)}^{2} \tag{4.16f}$$

$$\sum_{j=1}^{n} \lambda_{(j)}^{3*} Z_{(kj)} \geq Z_{(ko)} \tag{4.16g}$$

(4.16c), (4.16d), (4.16e), (4.16f) and (4.16g) are same as in $(same)$. Because $0 < \theta_{s1(o)} \leq 1$ from model $(s1)$, comparing (4.16a) and (4.16b) with (all), that is:

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{1*} X_{(ij)}^{1} \leq \theta_{some(o)}^{*} \theta_{s1} X_{(io)}^{1} \leq \theta_{some(o)}^{*} X_{(io)}^{1} \tag{4.17a}$$

$$\sum_{j=1}^{n} \bar{\lambda}_{(j)}^{1*} Y_{(lj)}^{1} \geq Y_{(lo)}^{1} \geq \theta_{s1} Y_{(lo)}^{1} \tag{4.17b}$$

(4.16a)-(4.16d) and (4.17a), (4.17b) imply that the feasible region of (all) is greater than $(some)$. Thus, $\theta_{all(o)}^{*} \leq \theta_{some(o)}^{*}$.

□

Hence, we have $\theta_{all(o)}^{*} \leq \theta_{some(o)}^{*} \leq \theta_{Network(o)}^{*}$.

4.3.5 Supply chain efficiency and CCR efficiency

Proposition 5 For the supply chain in which no suppliers can be replaced, the efficiency which calculated by model $(Network)$ is no larger than calculating by model $(Traditional)$, that is

$\theta_{Network(o)}^{*} \leq \theta_{T(o)}^{*}$

Proof. Suppose $\theta_{T(o)}^{*}, \lambda_{(j)}^{*}, j = 1, ..., n$ is an optimal solution to model $(Traditional)$. Let $\lambda_{(j)}^{1*} = \lambda_{(j)}^{2*} = \lambda_{(j)}^{3*} = \lambda_{(j)}^{*}, j = 1, \ldots, n$. It is obvious that $\theta_{T(o)}^{*}, \lambda_{(j)}^{1*}, \lambda_{(j)}^{2*}, \lambda_{(j)}^{3*}, j = 1, ..., n$ is also a feasible solution to model $(Network)$. Thus I have $\theta_{Network(o)}^{*} \leq \theta_{T(o)}^{*}$. □

Proposition 6 For the supply chain in which some suppliers can be replaced, the efficiency which calculated by model $(some)$ is no larger than calculating by model $(Traditional)$, that is

$\theta^*_{some(o)} \leq \theta^*_{T(o)}$

Proof. Suppose $\theta^*_{T(o)}, \lambda^*_{(j)}, j = 1, ..., n$ is an optimal solution to model $(Traditional)$. Let $\lambda^{1*}_{(j)} = \lambda^{2*}_{(j)} = \lambda^{3*}_{(j)} = \lambda^*_{(j)}, j = 1, \ldots, n.$ It is obvious that $\theta^*_{T(o)}, \lambda^{1*}_{(j)}, \lambda^{2*}_{(j)}, \lambda^{3*}_{(j)}, j = 1, ..., n$ is also a feasible solution to model $(some)$. Thus I have $\theta^*_{some(o)} \leq \theta^*_{T(o)}$. □

Proposition 7 For the supply chain in which all suppliers can be replaced, the efficiency which calculated by model (all) is no larger than calculating by model $(Traditional)$, that is

$\theta^*_{all(o)} \leq \theta^*_{T(o)}$

Proof. Suppose $\theta^*_{T(o)}, \lambda^*_{(j)}, j = 1, ..., n$ is an optimal solution to model $(Traditional)$. Let $\lambda^{1*}_{(j)} = \lambda^{2*}_{(j)} = \lambda^{3*}_{(j)} = \lambda^*_{(j)}, j = 1, \ldots, n.$ It is obvious that $\theta^*_{T(o)}, \lambda^{1*}_{(j)}, \lambda^{2*}_{(j)}, \lambda^{3*}_{(j)}, j = 1, ..., n$ is also a feasible solution to model (all). Thus I have $\theta^*_{all(o)} \leq \theta^*_{T(o)}$. □

4.4 Summary of the proposed model

Besides the specialty of the proposed models which struct from potential supply chain, mathematical proofs are also provides to show relationships with the previous models. In efficiency analysis section, the proposition 1-3 report the relationship of supply chain performance from model $(Network)$, $(some)$ and (all) with each member performance. I can conclude that those supply chains are inefficient if one if their members are inefficient. The proposition 4 reports the relationship between model $(Network)$ and the proposed model. And the propositions 5-7 present the relationship of the model $(Traditional)$ and the proposed models. I also can conclude that the proposed models provide a better tool to identify inefficient supply chains, among those some, i.e. $(Traditional)$ and $(Network)$.

4.5 Experiments with Empirical Data

A simple example is employed to explain the previous discussion. Suppose there are two supply chain, namely, SC_1 and SC_2. Each chain SC_s (s=1, 2) includes three members: Suppliers $S1_s$, Supplier $S2_s$ and Manufacturer M_s. The related input of each supplier (X^1, X^2), intermediate product (Y^1, Y^2) ,final output (Z) and theirs efficiency scores by model $Network$ are attainable as in table 4.1.

Table 4.1 shows that in SC_1, Supplier $S1_1$ consumes 4 units of inputs to produce 3 units of intermediate products, Supplier $S2_1$ consumes 2 units of inputs to produce 3 units of intermediate products, and Manufacturer M_1 uses both intermediates products to produce 10 units of final outputs. In the other supply chain SC_2, an

Table 4.1 – Empirical data set of example supply chains

Supply chain No.	X_1	X_2	Y_1	Y_2	Z	$\theta_{Network}$
SC_1 $(S1_1+S2_1+M_1)$	4	2	3	3	10	0.67
SC_2 $(S1_2+S2_2+M_2)$	3	3	3	4	15	1.00

operation data set is also shown in the same way. The efficiency scores of chain SC_1 by model $Traditional$ and $Network$ are 0.86 and 0.67 respectively. The efficiency scores of chain SC_2 by model $Traditional$ and $Network$ are also 1.00 and 1.00 respectively. By these efficiency scores, they show that the supply chain SC_1 is on an efficiency frontier.

4.5.1 Situation in which some suppliers are non-contracted

In this subsection, it assumes that suppliers $S2$ are non-contracted suppliers. As the above mentioned that the non-contracted suppliers are allowed to change with others, virtual supply chains which are created by changing non-contracted ones are considered. The virtual supply chains VSC_s in which consists by suppliers of other chains are created manually. To change the suppliers $S2$, their efficiency scores are utilized to change under the CRS consumption. The efficiency scores of Suppliers $S2$ are calculated by the model $(s2)$. The efficiency scores of $S2$ are shown in table 4.2. Table 4.3 shows two sets of virtual supply chain $VSCs$.

Table 4.2 – Suppliers $S2$'s efficiency score of example supply chains

Suppliers of	θ_{s2}
SC_1	1.00
SC_2	0.88

Table 4.3 – Test data set of the virtual supply chains by changing $S2$

Supply chain No.	X_1	X_2	Y_1	Y_2	Z
VSC_1 $(S1_1+S2_2+M_1)$	4	2.27 $(2\times\frac{1}{0.88})$	3	3	10
VSC_2 $(S1_2+S2_1+M_2)$	3	2.64 (3×0.88)	3	4	15

In table 4.3, all possibility virtual chains are presented. The virtual chain VSC_1 consists of supplier $S2_2$ and the virtual chain VSC_2 consists of supplier $S2_1$. After all possibility chains are created, the model $(Network)$ is used normally to measure efficiency of the current chains (SC_1, SC_2) and the virtual chains (VSC_1, VSC_2). The efficiency of chains is shown in table 4.4.

In the situation in which some suppliers are non-contracted, the model $(some)$ is

Table 4.4 – Efficiency scores of the current and virtual chains by changing $S2$

Supply chain No. $S2$	$\theta_{Network}$
SC_1	0.59
SC_2	0.88
VSC_1	0.52
VSC_2	1.00

used. Table 4.5 shows the efficiency scores which are calculated by the model $(some)$.

Table 4.5 – Efficiency scores by using the model $(some)$

Supply chain No. $S2$	θ_{some}
SC_1	0.59
SC_2	0.88

By using the model $(some)$, the virtual chains are created and compared automatically. It means the model $(some)$ allows appraisers to compare efficiency of the current chains and the virtual chains in the same times for situation that some suppliers are non-contracted.

4.5.2 Situation in which all suppliers are non-contracted

In this subsection, we assume that both suppliers are non-contracted $(S1$ and $S2)$. Then efficiency scores of supplier $S1$ and $S2$ are calculated by the models $(s1)$ and $(s2)$. The efficiency scores of both suppliers are shown in table 4.6.

Table 4.6 – Suppliers $S1$'s and $S2$'s efficiency score of example supply chains

Suppliers of	θ_{s1}	θ_{s2}
SC_1	0.75	1.00
SC_2	1.00	0.88

The virtual chains in this case are created by considering all possible structures. Table 4.7 shows all possibility virtual supply chain VSC_s.

After all possibility chains are created, the model $(Network)$ is used normally to measure efficiency of the current chains (SC_1, SC_2) and the virtual chains $(VSC_3, VSC_4, VSC_5, VSC_6)$. The efficiency of chains is shown in table 4.8.

In the situation in which all suppliers are non-contracted, the model (all) is used. Table 4.9 shows the efficiency scores which are calculated by the model (all).

Table 4.7 – Test data set of the virtual supply chains by changing $S1$ and $S2$

Supply chain No.	X_1	X_2	Y_1	Y_2	Z
VSC_3 $(S1_1 + S2_2 + M_1)$	4	1.76 (2×0.88)	3	3	10
VSC_4 $(S1_2 + S2_1 + M_1)$	9.39$(4 \times \frac{1}{0.75}$	2	3	3	10
VSC_5 $(S1_1 + S2_2 + M_2)$	2.25 (3×0.75)	3	3	4	15
VSC_4 $(S1_2 + S1_2 + M_2)$	3	3.41 $(3\times\frac{1}{0.88})$	3	4	15

Table 4.8 – Efficiency scores of the current and virtual chains by changing $S1$ and $S2$

Supply chain No. $S2$	$\theta_{Network}$
SC_1	0.59
SC_2	0.88
VSC_3	0.35
VSC_4	0.68
VSC_5	0.66
VSC_6	1.00

Table 4.9 – Efficiency scores by using the model (all)

Supply chain No. $S2$	θ_{some}
SC_1	0.59
SC_2	0.88

By using the model (all), the virtual chains are created and compared automatically. It means the model (all) allows appraisers to compare efficiency of the current chains and the virtual chains in the same times for situation that all suppliers are non-contracted.

4.6 Conclusion

The core models to this thesis have been presented in this chapter. This proposed models can be used to the supply chains consider replaceable and irreplaceable suppliers. For supply chain in which some suppliers are replaceable can be obtained from the model $(some)$. Additionally, supply chain in which all suppliers are replaceable can be applied by the model (all). In this chapter, the major contribution is the development of DEA approach for supply chain efficiency evaluation that combine replaceable suppliers. In the next chapter, an application of the proposed models shows with a case study of Thai frozen food industry.

5 Experiments: Supply chain of Thai frozen food industry

In Chapter 2, the fundamental of supply chain management, supply chain performance and applications of DEA model are introduced. The result from literature review shows that existing DEA models for supply chain efficiency evaluation still have gaps for considering an internal relationship of each member. The proposed models to deal with internal relationship have been discussed in the previous chapter.

In this chapter, the applicability of the proposed models for situation that chain includes different types of suppliers is shown. Supply chain of Thai frozen food industry is brought as case study due to its supplier type corresponding to the above mentioned situation.

5.1 Introduction

As noted in Chapter 2, DEA has proved to be a useful tool in evaluating relative performance of DMUs in a multiple-input multiple-output setting including as an application on supply chain efficiency evaluation. A Network DEA has been proposed to measure an efficiency of supply chain with complex structure. Generally, DEA estimates the efficiency index by calculating the ratio of weighted outputs to weighted inputs, and the input and output weights are decided according to the best interests of the DMU being evaluated [28]. This indicates that the conventional DEA does not consider a relationship between members in chain. In the other hand, SCM main idea is to enhance organizational productivity and profitability by considering cooperation between members in chain. These are contrast of conventional DEA and supply chain management. As noted in Chapter 3,an alternative method is proposed to combine a contrast of SCM and DEA together. a case study, Thai exported frozen food industry supply chain, is also provided to illustrate an using of the proposed models. Two types of supply chains, frozen shrimp and frozen vegetable, are applied with the proposed models and their efficiency are measured. In section 2, the efficiency of the exported frozen food supply chain is presented to understand basic of this supply chain first. Then, its structure is presented in section 3 to show a compatible with a structure which introduced in the proposed method. In section 4, steps of apply the proposed method to case study is explained. An application of the method to case study is presented in Section 5. Section 6 provides discussions and conclusions.

In the South East Asia, Thailand is recognized as one of the main agricultural countries in not only the region but in the world. Many agricultural products have been the potential to export to the world market. Vegetables, fruits, meats and seafood are exported, values over a billion yearly. Such products are positioned as high-quality exported products. They are exported in a chilled and frozen form. The frozen food industry is considered an important industry in Thailand due to its high value, volume, and also produced form domestic products [21]. That means all the activities of this industry covers many area especially in the part for farmers. The type of these products that are differences from other by limitation of harvesting period and shelf life, which are first priority to prevent the damage, unpredictable risk in production. Besides the firms need to understand the exporting process as well. With these causes, supply chain structure is more complex. And for the efficiency measurement, the inputs and outputs are considers as priority especially inputs which have high risk of damage because almost of them are fresh products. Besides, the structure of this supply chain, suppliers are categorized into two types, contacted one and non-contracted one [19]. Contracted suppliers have to deliver products to the manufacturers stable under the contract. Whereas non-contacted one can be replaced anytime. It means non-contracted suppliers need to improve their efficiency or they could be changed by the manufacturers. Regarding to the above mentions, Thai frozen food industry supply chain is used as case study of this research.

5.2 The efficiency of supply chain management of the exported frozen food

In recently, performance evaluation and metrics for SCM have received much concentration from academics and practitioners. To improve performance system in a supply, all members in the supply chain should be involved and committed to common goals. There are many researches applied the efficiency or performance measurement system to the difference kind of organization and firms. And in 2009, Chaowarat [21] introduced the measurement system for the frozen food industry. In this research, dimensions of exported frozen food industry as shown

Figure 5.1 – The efficiency dimension of frozen food industry supply chain

in shown in Fig. 5.1 are:

1. Efficiency in the dimensions of the efficiency and process management in organization
   An ability of using resources for producing the benefit is considered. How much benefit and value each firm can produce from their existing resources towards work to correcting the standard to be fast and easier.

2. Efficiency in the dimensions of quality
   The quality efficiency for exported frozen food is grouped into 2 parts. The two parts are about processes and products. In the process part, there are definite criteria, especially for exported food that firms have to be qualified for export standards. So in this dimension is emphasized on the quality in production processes.

3. Efficiency in dimensions of collaboration between organizations
   Because the main idea of supply chain management is management among the members in the supply chain. Therefore, the cooperation between the firms should be observant. Including the agricultural product which most of quantity and quality of products depending on the suppliers thus the management among firms should be given particular emphasis.

5.3 The exported frozen food supply chain structure

In 2010, Chaowarat [21] studied the structure of exported frozen food supply chain and performance and the frozen food supply chain structure could be drawn as Fig. 5.2.

Farmers are considered as the main suppliers of frozen food industry and can be categorized into three types, which are independent farmers, hired farmers, and farmers with contract farming. For the independent farmers, they have to

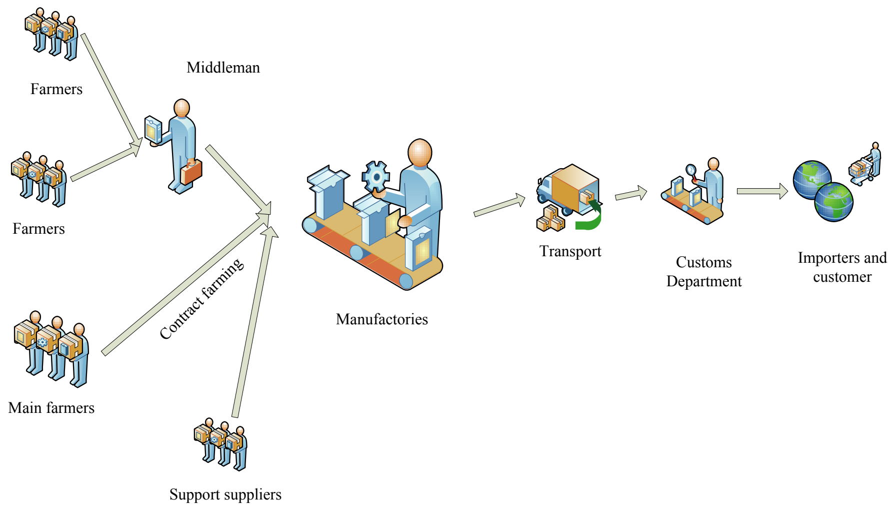


Figure 5.2 – The members of frozen food industry supply chain
Source: [20]

plan to produce the product by themselves and prepare materials and plan their production by themselves, and as well as to sell the product to the factory. The hired farmers are also similar to independent farmers,but only that they will get wage form the factories apart from the price of the product. For contracted farmers, the factories will provide support in terms of planting which is in the processed factory (such as seeds, planting preparation, fertilizer and herbicide), time specification and plant and harvest quantity factors. The middleman or broker responds to be an agent between the factory and agriculturist in the case of non-contracted farmers. The support supplier is another supplier who supplies other materials related to the production, such as package, plastic, breeders, animal food or any other product associated to the production.

In this chain, manufacturing is a function of producing the frozen food. Operation process of processed food factory begins with the material demand planned from the purchasing order and sourcing. After that, material will be put into the process depending on the food type and then examine the product quality randomly again. If there is nothing wrong about the product, it will be delivered to the transporting organization in order to send it to the harbor. In the meantime, the factory needs to contact the shipping organization to receive the product and send to the harbor delivering internationally. As it is exported, this kind of product concern sanitary, the export procedures need to be examined from the Customs Department. The processes are different depending on the types of products that are available on the website of Customs Department.

5.4 Methodology

The methodology proposed here is described in Fig. 5.3. In this research, there are two phases contained in this methodology. The first phase is preparing data for measurement (refer to step 1). This phase comprises of constructing supply chain structure and determining criteria to represent inputs and outputs including gathering data. The second phase is efficiency evaluation (refer to step 2 to 4). In efficiency evaluation phase, first an efficiency of supplier is identified by traditional DEA model, and the model which includes suppliers' efficiency is applied for an efficiency of chain. The structure which is used in this paper is displayed in Fig. 5.4 as follow;

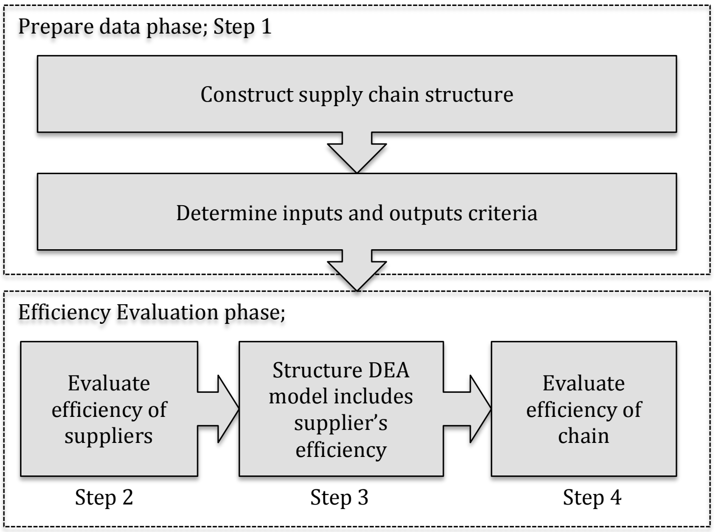


Figure 5.3 – Outline of research methodology

For the simplicity, a two stage supplier-manufacture chain is consider as following in Fig. 5.4, where $S1, S2$ and M represent the constant supplier, the changeable supplier and the manufacturer, respectively. X^1 and X^2 stand for inputs of supplier 1 ($S1$) and supplier 2 ($S2$) respectively. Intermediate products of $S1$ and $S2$ are Y^1 and Y^2 accordingly. And final output is Z.

Step 1: Determine inputs and outputs criteria.

In this step, comprehensive literature reviews are used for studying performance criteria and choosing the primary criteria of measurement. After getting primary criteria, interviews with experts are provided. The experts had been involved in supply chain projects more than five years, the government officials who had had experience in planning policy on supply chain and logistics and scholars who had worked on supply chain management and logistics for more than 5 years. To gather data in which is related to

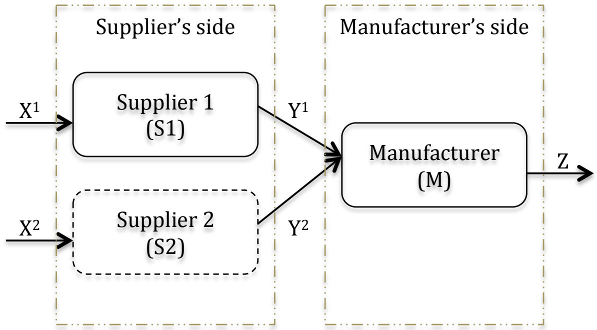


Figure 5.4 – Structure of chain for frozen food industry

performance criteria, an interview approach is used.

According to the supply chain structure as shown in Fig. 5.4, in the supplier stage, both suppliers consume some inputs such as Fixed Assets (FA), Production Capacity (PC) and Inventory & Transportation Cost (ITC) to generate Damage Rate (DR) and Supplier On-time Rate (SOR). In the manufacturer stage, DR and SOR are used to produce Returns On Assets (ROA) and Returned Products (RP) as in table 5.1.

Table 5.1 – Measurement criteria

Inputs (X)	Intermediate products (Y)	Outputs (Z)
Fixed Assets (FA)	Damage Rate (DR)	Returns On Assets (ROA)
Production Capacity (PC)	Supplier On-time Rate (SOR)	Returned Products (RP)
Inventory & Transportation Cost (ITC)		

Step 2: Measure efficiency of replaceable suppliers.

After the efficiency criteria are selected and data is gathered, replaceable suppliers are measured efficiency. In case that all suppliers are replaceable, suppliers are measured efficiency by their model. In this research assume that there are two members, s1 and s2, in chain regarding to Fig. 5.4. Their models are presented as follow;

$$(s1)\left|\begin{array}{ll} \text{minimize} & \theta_{s1(o)} \\ subject\ to & \sum_{j=1}^{n} \lambda^{1}_{(j)} X^{1}_{(ij)} \leq \theta_{s1(o)} X^{1}_{(io)} \\ & \sum_{j=1}^{n} \lambda^{1}_{(j)} Y^{1}_{(lj)} \geq Y^{1}_{(lo)} \\ & \lambda^{1}_{(j)} \geq 0 \end{array}\right.$$

$$(s2)\left|\begin{array}{ll} \text{minimize} & \theta_{s2(o)} \\ subject\ to & \sum_{j=1}^{n} \lambda^{1}_{(j)} X^{2}_{(ij)} \leq \theta_{s2(o)} X^{2}_{(io)} \\ & \sum_{j=1}^{n} \lambda^{1}_{(j)} Y^{2}_{(lj)} \geq Y^{2}_{(lo)} \\ & \lambda^{2}_{(j)} \geq 0 \end{array}\right.$$

In other hand, in case that some suppliers can be replaceable, only replaceable supplier is measured in this step. For example, $s2$ is assumed as replaceable supplier, then in this step only model $(s2)$ is used.

Step 3: Structure DEA model includes replaceable supplier's efficiency,

After replaceable supplier's efficiency is measured, its efficiency is included in the overall efficiency by applying replaceable supplier's efficiency in production possibility set. In case that all suppliers can be changed, its productions possibility is expressed as follows.

$$\begin{aligned} T_{all} = \{(X^{1}_{(io)}, X^{2}_{(io)}, Y^{1}_{(lo)}, Y^{2}_{(lo)}, Z_{(ko)}) | & \sum_{j=1}^{n} \lambda^{1}_{(j)} \theta_{s1(o)} X^{1}_{(ij)} \leq X^{1}_{(io)}, \sum_{j=1}^{n} \lambda^{1}_{(j)} Y^{1}_{(lj)} \geq Y^{1}_{(lo)}, \\ & \sum_{j=1}^{n} \lambda^{2}_{(j)} \theta_{s2(o)} X^{2}_{(ij)} \leq X^{2}_{(io)}, \sum_{j=1}^{n} \lambda^{2}_{(j)} Y^{2}_{(lj)} \geq Y^{2}_{(lo)}, \\ & \sum_{j=1}^{n} \lambda^{3}_{(j)} Y^{1}_{(lj)} \leq Y^{1}_{(lo)}, \sum_{j=1}^{n} \lambda^{3}_{(j)} Y^{2}_{(lj)} \leq Y^{2}_{(lo)}, \\ & \sum_{j=1}^{n} \lambda^{3}_{(j)} Z_{(kj)} \geq Z_{(ko)}, \lambda^{1}_{(j)}, \lambda^{2}_{(j)}, \lambda^{3}_{(j)} \geq 0\} \end{aligned}$$

The production possibility set in which some suppliers are replaceable is shown as;

$$
\begin{aligned}
T_{some} = \{((X^1_{(io)}, X^2_{(io)}, Y^1_{(lo)}, Y^2_{(lo)}, Z_{(ko)}) | \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \leq X^1_{(io)}, \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)}, \\
\sum_{j=1}^{n} \lambda^2_{(j)} \theta_{s2(o)} X^2_{(ij)} \leq X^2_{(io)}, \ \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)}, \\
\sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)}, \ \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)}, \\
\sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)}, \ \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \geq 0\}
\end{aligned}
$$

Step 4: Measure efficiency of chain by model from step 3. Since the production possibility set is decided, the chain efficiency is measured by following model;

$$
(all) \left|
\begin{array}{ll}
\text{minimize} & \theta_{all(o)} \\
\textit{subject to} & \theta_{all(o)} X^1_{(io)} - \sum_{j=1}^{n} \lambda^1_{(j)} \theta_{s1(o)} X^1_{(ij)} \geq 0 \\
& \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \\
& \theta_{all(o)} X^2_{(io)} - \sum_{j=1}^{n} \lambda^2_{(j)} \theta_{s2(o)} X^2_{(ij)} \geq 0 \\
& \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)} \\
& \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \geq 0
\end{array}
\right.
$$

and

$$
(some)\quad
\begin{array}{|ll}
\text{minimize} & \theta_{some(o)} \\
subject\ to & \theta_{some(o)} X^1_{(io)} - \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \geq 0 \\
& \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \\
& \theta_{some(o)} X^2_{(io)} - \sum_{j=1}^{n} \lambda^2_{(j)} \theta_{s2(o)} X^2_{(ij)} \geq 0 \\
& \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)} \\
& \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)} \\
& \lambda^1_{(j)}, \lambda^2_{(j)}, \lambda^3_{(j)} \geq 0
\end{array}
$$

where model (all) is model of supply chain that all suppliers are replaceable, and model $(some)$ stands for model for supply chain which some suppliers are replaceable.

In order to show the effectiveness of the proposed models, an example of frozen shrimp industry supply chain are shown in this section. All sample group are members of Thailand Institute of Scientific and Technological Research (TISTR), Food Technology Department.

5.5 Case study : Frozen shrimp industry

In this industry, it is necessary for a manufacturer to receive raw materials from many suppliers due to difficulties of resourcing which are caused by unstable production. In this type of supply chain, there are two types of suppliers which are contracted and non-contracted one. As described above, non-contracted supplier can be replaced freely but contracted ones cannot be.

When data according to step 1 is collected, the replaceable suppliers (s2) of each chain is measured by the model $(s2)$. After the efficiency of replaceable supplier is measured, decreasing of inputs to be efficient supplier is also identified. To create virtual efficient supplier, its efficiency score is multiplied with original input data. Due to concept that the replaceable supplier is allowed to switch to be efficient one, input data from this step is used to measure an efficiency of chain.

Table 5.2 – Data sets of the frozen shrimp industry samples

DMUs		FA (10^6 THB)	PC (10kg/3.95 Acres)	ITC (%)	DR (%)	SOR (%)	ROA	RP (%)
1	s1	8.21	271.30	42.50	97.14	96.18	0.36	9 8.53
	s2	7.49	306.90	42.50	96.63	93.23		
2	s1	12.05	306.90	42.50	96.93	95.27	0.66	9 6.92
	s2	4.46	271.30	42.50	96.49	92.23		
3	s1	12.06	282.80	40.00	97.12	96.03	1.23	9 8.62
	s2	6.58	306.90	40.00	95.00	91.88		
4	s1	13.40	271.30	45.00	97.62	94.24	2.33	97.65
	s2	7.67	271.30	43.00	96.00	91.09		
5	s1	14.11	373.80	45.00	96.97	95.20	2.72	97.08
	s2	4.97	373.80	47.00	96.56	91.83		
6	s1	16.51	306.90	47.00	98.22	95.57	3.41	97.18
	s2	5.20	282.80	42.50	96.40	91.68		
7	s1	20.37	271.30	42.50	97.69	93.97	3.46	97.74
	s2	6.00	373.80	45.00	96.62	91.59		
8	s1	21.03	373.80	42.50	97.39	94.90	3.97	97.31
	s2	5.24	282.80	42.50	96.04	91.79		
9	s1	24.42	347.30	32.50	97.08	94.39	3.97	98.42
	s2	4.89	271.30	35.00	96.39	92.29		
10	s1	27.87	306.90	35.00	98.04	95.58	4.31	97.45
	s2	4.68	347.30	40.00	96.91	91.85		
11	s1	29.04	309.50	45.00	97.14	95.96	4.71	97.68
	s2	5.45	306.90	45.00	96.05	91.53		
12	s1	29.85	282.80	43.00	97.17	94.71	9.79	98.06
	s2	4.03	282.80	47.00	95.89	92.34		
13	s1	36.59	373.80	42.50	96.96	95.47	10.08	97.61
	s2	4.00	373.80	42.50	95.57	92.44		
14	s1	37.41	282.80	40.00	96.77	95.55	16.86	97.35
	s2	3.95	309.50	35.00	96.30	91.42		
15	s1	38.60	271.30	42.50	97.69	94.41	18.43	98.12
	s2	3.51	271.30	40.00	96.99	92.45		

After determining and applying suppliers efficiency, an overall efficiency of chain is evaluated. The data set which is used in this step and efficiency of chain is shown in table 5.3.

Table 5.3 reports the efficiency scores of each suppliers (s_1, s_2) and supply chain by traditional DEA ($Traditional$), Network DEA ($Network$), the proposed models ($(some), (all)$). For potential supply chain if which there are contracted and non-contracted suppliers, then the model $(some)$ is brought to evaluate supply chain efficiency. In second column, which shows an efficiency score of non-contracted

Table 5.3 – Efficiency results of frozen shrimp supply chain

DMUs	$\theta_{s1(o)}$ by (s1)	$\theta_{s2(o)}$ by (s2)	$\theta_{T(o)}$ by (Traditional)	$\theta_{Network(o)}$ by (Network)	$\theta_{some(o)}$ by (some)	$\theta_{all(o)}$ by (all)
1	1.000	0.884	1.000	1.000	1.000	1.000
2	0.949	0.999	1.000	1.000	0.995	0.993
3	1.000	0.880	1.000	1.000	1.000	1.000
4	1.000	1.000	1.000	1.000	1.000	1.000
5	0.884	0.806	0.883	0.882	0.882	0.882
6	0.902	0.957	0.975	0.953	0.927	0.925
7	1.000	0.791	1.000	0.994	0.994	0.923
8	0.890	0.962	0.954	0.952	0.951	0.950
9	1.000	1.000	1.000	1.000	1.000	1.000
10	1.000	0.923	1.000	1.000	1.000	1.000
11	0.904	0.878	0.909	0.903	0.903	0.902
12	0.972	0.959	0.996	0.968	0.968	0.953
13	0.823	0.925	0.949	0.910	0.910	0.905
14	0.996	1.000	1.000	1.000	1.000	1.000
15	1.000	1.000	1.000	1.000	1.000	1.000

suppliers (s2), the result shows that the non-contracted suppliers of chain 4, 9, 14 and 15 are efficient, and it means there are only 4 efficient suppliers among 15 suppliers. By using the traditional DEA which all processes in a system is considered as black box, the result shows that there are only 6 inefficient chains from 15 chains while there are 7 inefficient chains from 15 chains computed by network DEA model. By using the model $(some)$, 8 supply chains among all supply chains have been found inefficient. This result leads to the conclusion that the model $(some)$ can identify inefficient supply chains extensively based on accurate structure of the food supply chain.

As above mentioned that non-contracted suppliers are allowed to compare their efficiency first because they need to improve their efficiency otherwise they could be changed by the manufacturers. In case that contracted suppliers are allowed to compare their efficiency first as same as non-contracted one, the model (all) is utilized. By this model, the efficiency score of contracted suppliers are shown in first column. The result shows that the contracted suppliers (s1) of chain 1, 3, 4, 7, 9, 10 and 15 are efficient. Compared with non-contracted one, it shows that number of efficient contacted suppliers are more than non-contracted one. By using the model (all), there are 8 inefficient chains among all supply chains as same as the result from the model $(some)$. Although number of inefficient chains from the two model are the same, the efficiency scores of the model (all) are always equal or less than the ones from the model $(some)$. Thus, the model (all) can identify inefficient supply chains extensively in case that all suppliers are considered replaceable ones. In addition, a potential supplier can be given in order to emphasize an inherent of efficiency improvement at the same time.

5.6 Case study : Frozen vegetable industry

In this case study, a comparison of all models which are *traditional*, *network*, *some* and *all* models is shown. Base on case study, all suppliers have contracted which manufacturers which means all suppliers are irreplaceable. This concludes that only the network DEA model satisfies this type of suppliers. But in case that an efficiency of supplier is considered, model (*some*) and (*all*) are utilized. The data regarding to inputs and outputs criteria from step 1 is shown in table 5.4

Table 5.4 – Data sets of the frozen vegetable industry samples

DMUs		FA (10^6 THB)	PC	ITC (%)	DR (%)	SOR (%)	ROA	RP (%)
1	S1	61.70	96.48	40.00	99.50	99.00	5.37	97.50
	S2	7.35	96.48	37.00	98.50	93.00		
2	S1	39.52	95.66	42.50	98.00	93.00	4.39	98.00
	S2	15.65	94.23	30.00	99.50	98.50		
3	S1	8.91	94.17	35.00	98.50	92.50	5.78	98.00
	S2	11.04	97.34	32.50	99.50	95.00		
4	S1	3.03	97.34	32.50	97.00	90.00	7.31	99.00
	S2	1.72	95.66	45.00	98.50	97.00		
5	S1	14.73	96.48	40.00	98.00	95.00	0.84	98.00
	S2	0.41	90.00	37.00	97.50	92.75		
6	S1	18.38	95.66	35.00	98.50	97.50	4.04	98.00
	S2	9.42	96.48	45.50	99.00	95.00		
7	S1	10.16	94.17	42.50	98.00	95.00	0.43	98.00
	S2	0.09	95.66	47.00	98.00	92.50		
8	S1	4.11	96.48	40.00	96.50	90.00	1.25	97.00
	S2	2.11	96.35	42.50	98.00	97.00		
9	S1	27.87	97.34	37.00	99.00	97.50	3.86	98.00
	S2	0.53	93.45	47.00	97.50	92.50		

After determining and applying suppliers efficiency, an overall efficiency of chain is evaluated. The data set which is used in this step and efficiency of chain is shown in table 5.5.

Table 5.5 shows an efficiency score of frozen vegetable supply chains. Based on an actual vegetable supply chain consists of two type s of suppliers. Then first

Table 5.5 – Efficiency results of frozen vegetable supply chain

DMUs	$\theta_{s1(o)}$ by (s1)	$\theta_{s2(o)}$ by (s2)	$\theta_{T(o)}$ by (Traditional)	$\theta_{Network(o)}$ by (Network)	$\theta_{some(o)}$ by (some)	$\theta_{all(o)}$ by (all)
1	1.00	0.95	1.00	0.98	0.98	0.97
2	0.98	1.00	1.00	1.00	1.00	1.00
3	1.00	1.00	1.00	1.00	1.00	1.00
4	1.00	0.98	1.00	1.00	1.00	0.99
5	0.98	1.00	1.00	1.00	1.00	0.99
6	1.00	0.95	0.99	0.99	0.99	0.98
7	1.00	1.00	1.00	1.00	1.00	1.00
8	1.00	0.98	1.00	0.99	0.99	0.97
9	0.99	0.96	1.00	0.98	0.98	0.96

the model $(some)$ is applied. The third column shows efficiency scores score of supplier 2 (s2) which are non-contracted ones. The third, forth and fifth columns exhibit efficiency scores of supply chains under the $(Traditional)$, $(Network)$, and $(some)$ models, respectively. For $s2$, there are 5 supplier are found inefficient. By both suppliers efficiency score, only two chains consist efficient suppliers which are 3 and 7 chain. After efficiency score of suppliers are defined, an overall efficiency is determined. Under the traditional DEA model which all processes in a system is considered as black box, only one inefficient from 15 supply chains was found. When there are 4 inefficient chains with computed by network DEA model. By using the model $(some)$, 4 chains are found inefficient as same as in the network model.

In the same way as frozen shrimp supply chain, all suppliers are assued to be replaceable to allows them to compare theirs efficiency first. In second column, efficiency score of supplier 1 is shown. The result shows that $s1$ of chain 2, 5 and 9 are inefficient. In comparing of both suppliers types, it means number of efficient contracted suppliers is greater than number of efficient non-contracted ones. By using the model (all) which assumes all suppliers can be replaced, 6 inefficient chains are found .

5.7 Summary of result

To evaluate an efficiency of potential agricultural supply chain, the model $(some)$ is utilized because, generally, suppliers of agricultural supply chain are contracted and non-contracted suppliers in the same chain. For the frozen shrimp industry, 8 inefficient chains among all supply chain have been found by model $(some)$ while only 4 and 5 inefficient chains computed by the conventional models. For the frozen vegetable industry, there are 4 inefficient chains under-computed by model $(some)$ and $(Network)$ while there are only one inefficient chain with the traditional model.

Under the assumption in which all suppliers can be replaceable, the model (all) allows suppliers efficiency to measure first. Each suppliers' efficiency are allowed to analyze their effects on chain efficiency. Under computing by the model (all), there are seven inefficient chains in frozen shrimp chains and six chains in frozen vegetable chains. The result confirms that the proposed method can identify inefficient supply chains extensively based on accurate structure of the frozen food supply chain. In addition, a potential supplier can be given to emphasize an inherent of efficiency improvement at the same time.

Besides, comparing efficiency between types of suppliers, it is obvious that contracted suppliers (irreplaceable suppliers or s1) are more efficient than non-contracted suppliers (replaceable suppliers or s2) in both frozen shrimp and vegetable supply chains. This result confirms the fact that the manufacturers would tend to choose efficient suppliers to be theirs contracted supplier for stability of their productions.

5.8 Discussions and conclusions

In this chapter, models to evaluate efficiency of supply chain considering replaceable supplier have been proposed to Thai frozen food industry supply chain. A case study approach is used to illustrate an appropriateness of the proposed models.

The two case studies evidence that we can conclude that :

(i) The supply chain efficiency score from the proposed models is not larger than the efficiency score from the traditional DEA and the network DEA. This result shows that the proposed model can find inefficient chains effectively than two traditional models.

(ii) The supply chain efficiency score from both proposed models $(\theta_{some(o)})$ or $(\theta_{all(o)})$ is not larger than the product of each member efficiency $(\theta_{s1(o)} * \theta_{s2(o)} * \theta_M)$. We can also conclude that those supply chains are inefficient if one of its members are inefficient.

(iii) The proposed models provide an alternative target for inefficient supply chain to improve its suppliers. For example, in chain 7 of the frozen shrimp supply chain which its changeable supplier is inefficient, the model allows us to see if chain 7 can improve its supplier to be efficient (based on suppliers of chain 4,9,14 and 15). That means in case that chain 7 should consider changeable suppliers of chain 4,9,14 and 15 as its goal first.

6 Applications on Customers' Satisfaction

In Chapter 4, the applicability to consider customers' satisfaction of the proposed model for situation some suppliers in a chain are non-contracted is shown.

6.1 Introduction

Considering customers' satisfactions is one of important topics of SCM because an important of SCM is to satisfy customers' requirements. Besides, it is also one of key factors determining how good the organization will be in customer relationships [73]. Customers' satisfaction is defined as "the number of customers, or percentage of total customers, whose reported experience with a firm, its products, or its services (ratings) exceeds specified satisfaction goal" [46]. Customers' satisfaction would bring profit to a company which also brings employees' satisfaction; hence, organizations need to understand that what improve their customers' satisfaction [73]. To improve the customers' satisfaction, the organizations have to evaluate their efficiency to fulfill customers' requirements and identify their customers' satisfaction.

Customers' satisfaction is a person's feelings of pleasure or disappointment resulted from comparing a product's perceived performance in relation to his or her expectations [57]. Customers' satisfaction or dissatisfaction is considered as a measurement of a gap between customers' expectations and performance outcomes of organizations, where negatively disconfirmed expectations lead to dissatisfaction [35, 74, 76]. One of important responses from a customer is 'customer complaints' hence they are reports of problems or failures in processes which need quick recovery in order to avoid migration of profitable customers [70]. Branes [12] mentioned that "a typical business only hears from 4% of its dissatisfied customers, the other 96% leave, 91% for good." That is obvious that complaints which are received from customer are reflected customers' satisfaction directly.

In agricultural supply chain, the main cause for customers' complaints are from production and quality of products. Usually, this chain consists of a manufacturer and several suppliers. On the suppliers' side, farmers are focused as main suppliers because main materials are produced by them. The farmers' productivity depends on cultivation that relies heavily on its surroundings, natural disasters, plagues, pests and even on labor variations in different regions, resulting in differences in the numbers of workers and in the convenience of shipments between farmers and factories. All of these factors lead to difficulties for stable production. They also affect the products' quality and overall efficiency of a chain.

Because there are several suppliers, the manufacturer focuses to choose efficient suppliers to avoid unstable production and low quality products. In this type of chain, the manufacturer is connected with suppliers by inter product flow and suppliers' contracts. It means contracted suppliers have to deliver products to the manufacturer stably under the contract. On the other hand, non-contracted suppliers need to improve their efficiency or they could be changed by the manufacturers [19]. Therefore, the proposed method is suitable when discussing customers' satisfaction.

As mentioned in the Chapter 2 that the current DEA evaluate methods cannot use such usage because the existing methods cannot consider the situation in which some suppliers are changed. The alternative models are proposed to deal with this situation. In Chapter 3, the applicability of the proposed models has been investigated, and it has been confirm that the proposed models can identify inefficient supply chains extensively. In addition, an inefficient supply chain can be given to emphasize its efficiency in the case that its supplier is efficient. As mentioned above, usual agricultural supply chain consists of a manufacturer and several suppliers, and the manufacturer can change some of the suppliers in order to improve their customers' satisfaction. Then, the manufacturer has to evaluate performances of supply chains with possible suppliers. Therefore, this chapter, the ability of the method is discussed in the case that a manufacturer changes its inefficient supplier to improve their customers' satisfactions.

6.2 Customers' satisfactions

Customers' satisfaction has been a major goal for business organizations for many years and loyal customers contribute to the company's profitability by spending more on the company's products and services [39]. Kotler [57] defined customers' satisfaction as "the level of a person felt state resulting from comparing a product's perceived performance or outcome in violation to his/her own expectation." Customers' satisfaction is also defined as a comparative behavior between inputs beforehand and post obtainment [79]. From those definitions, customers' satis-

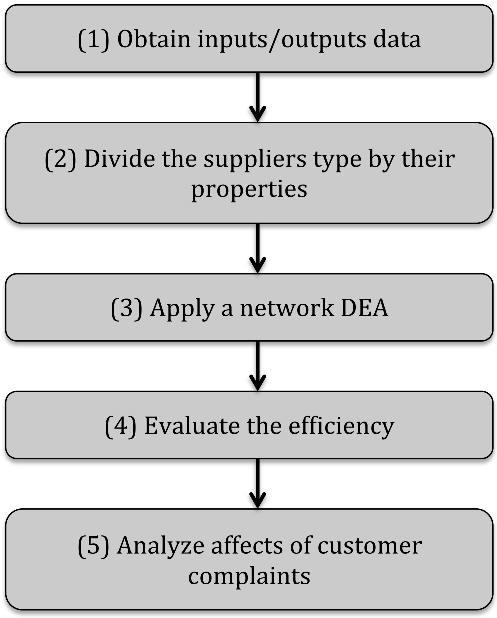


Figure 6.1 – Outline of research methodology

faction could be considered as customers' requirements that have been fulfilled. It does not reflects only the degree of customers' satisfaction, but also reflects companies' to provide products or services to meet customers' demands.

Dissatisfaction is another side of satisfaction regarding ways to remedy feelings of discomfort and related actions, such as complaining behavior [33, 76]. Oliver [76] explains dissatisfaction as "the consumers' fulfillment response and judgment that a product or service feature, or the product or service itself, provides (or is providing) a discomfort level of consumption-related fulfillment, including levels of under-fulfillment." 'Customer complaints' is one of important responses which represents customers' dissatisfaction. Indeed complaints provide managers with useful information to enhance service quality [25]. When dissatisfied customers fail to complain, companies are likely to miss the opportunity of redressing the type of the problem and that to learn about mistakes, through a feedback from dissatisfied customers [25]. As above mentioned, the customer complaints could be indications of organizations, hence they are reports of problems or failures in processes which are strongly required in order to avoid migration of profitable customers [70]. Since, customer complaints should be included in one of efficiency criteria in performance measurement.

6.3 Methodology

An outline of this chapter is illustrated in Fig. 6.1.

1. Input and output data, which represent the efficiency of each stage, are obtained.

2. All suppliers in chains are separated into two types, replaceable one and irreplaceable one.

3. The proposed network DEA model with replaceable suppliers concept will be applied.

4. The efficiency is measured by using the model generated in the previous step. Finally, the affect of suppliers and customer complaints on efficiency of chain is analyzed by comparing an efficiency of the chain which consists of an efficient supplier.

6.3.1 Supply chain structure

Generally, agricultural supply chain consists of a manufacture and several suppliers. Some suppliers are connected with a manufacturer by products flow and their contract while some are connected with a manufacturer by only product flow. Thus, in order to improve customers' satisfaction, a manufacturer can consider to change only non-contracted suppliers. To simplify the problem, a simple chain which has two suppliers and one manufacturer are conducted. Fig. 6.2 illustrates the idea step by step. The upper part of Fig. 6.2 shows an actual situation, the right part of this figure is supply chain part and the left part of this figure stands for customer one. In the supply chain side, $S1, S2$ and M represent the constant supplier, the changeable supplier and the manufacturer, respectively. X^1 and X^2 stand for inputs of supplier 1 $(S1)$ and supplier 2 $(S2)$ respectively. Intermediate products of $S1$ and $S2$ are Y^1 and Y^2 accordingly. And final output is Z. After customers get their products, they would send their complaints in a case that they do not satisfy the products or services. Since, their complaints can be regarded as an undesirable output for a supply chain as shown at the bottom part of Fig. 6.2.

6.3.2 The DEA model

The DEA model which has been used in this research is considered as the structure as shown in Fig. 6.2. The efficiency of chain can be computed using the following model:

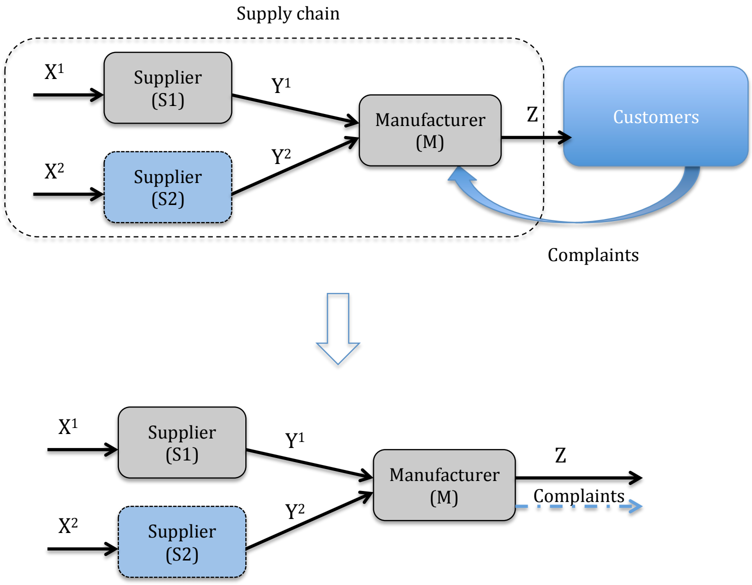


Figure 6.2 – Framework structure of supply chain with customers complaints

$$(some)\quad \begin{array}{|ll} \text{minimize} & \theta_{some(o)} \\ \text{subject to} & \theta_{some(o)} X^1_{(io)} - \sum_{j=1}^{n} \lambda^1_{(j)} X^1_{(ij)} \geq 0 \\ & \sum_{j=1}^{n} \lambda^1_{(j)} Y^1_{(lj)} \geq Y^1_{(lo)} \\ & \theta_{some(o)} X^2_{(io)} - \sum_{j=1}^{n} \lambda^2_{(j)} \theta_{s2(o)} X^2_{(ij)} \geq 0 \\ & \sum_{j=1}^{n} \lambda^2_{(j)} Y^2_{(lj)} \geq Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Y^1_{(lj)} \leq Y^1_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Y^2_{(lj)} \leq Y^2_{(lo)} \\ & \sum_{j=1}^{n} \lambda^3_{(j)} Z_{(kj)} \geq Z_{(ko)} \\ & \lambda^1_j, \lambda^2_j, \lambda^3_j \geq 0 \end{array}$$

Where

$\theta_{some(o)}$: Efficiency score of in-considering chain.

$\theta_{s2(o)}$: Efficiency score of changeable supplier in in-considering chain.

$X^1_{(ij)}$: Vector of *i*-th inputs of supplier 1's for *j*-th chain.

$X^1_{(io)}$: Vector of *i*-th inputs of supplier 1's for in-considering chain.

$Y^1_{(lj)}$: Vector of *l*-th intermediate products of supplier 1 in *j*-th chain.

$Y^1_{(lo)}$: Vector of *l*-th intermediate products of supplier 1 for in-considering chain.

$X^2_{(ij)}$: Vector of *i*-th supplier 2's inputs for *j*-th chain.

$X^2_{(io)}$: Vector of *i*-th supplier 2's inputs for in considering chain.

$Y^2_{(lj)}$: Vector of *l*-th intermediate products of supplier 2 in *j*-th chain.

$Y^2_{(lo)}$: Vector of *l*-th intermediate products of supplier 2 in in-considering chain.

$Z_{(kj)}$: Vector of *k*-th final outputs for manufacturer of *j*-th chain.

$Z_{(ko)}$: Vector of *k*-th final outputs for manufacturer of in-considering chain.

n : The number of chains.

By using this model, an effect of suppliers and customer complaints on efficiency of chain can be analyzed.

6.3.3 The advantage of the model

As the above mentioned situation, an efficiency of replaceable suppliers are not included in a measurement by using the traditional network DEA. Hence, the replaceable supplier efficiency cannot be investigated an effect of chain efficiency and customer complaints. By using the proposed model, an efficiency of replaceable supplier is investigated to show an efficiency of chain which consists of an efficient supplier. The proposed model leads us to inspect that which chain constructed by inefficient replaceable supplier. After choosing the chain which is needed to improve its supplier, the efficiency result of chain could be analyzed how the chain efficiency could be changed by improve replaceable supplier and contain same customers' complaints. For example, if the most inefficiency chain improves its suppliers which means it consumes less inputs system to produce same outputs, the chain will be efficient or not.

6.4 Experiment

As mentioned above, customer complaints are one of criteria which exhibit customers' satisfaction, an efficiency performance which includes customers' complaints should be estimated. In previous section, the network DEA model which includes an efficiency of replaceable supplier is proposed. The method has been applied in the frozen shrimp supply chains in Thailand. The samples are export factories, which are located in the southern and eastern parts of Thailand and comprise the members of the Thailand Institute of Scientific and Technological Research (TISTR), Food Technology Department. The criteria and datasets that are used in this evaluation are shown in Table 6.1 and 6.2.

Table 6.1 – Measurement Criteria

Construct	Criteria
Inputs (X)	X_1 : Fixed Assess (10^6 Baht)
	X_2 : Production Capacity (10kg per 3.95 Acres)
	X_3 : Inventory and Transportation Cost (%)
Intermediate Products (Y)	Y_1 : Damage Rate (%)
	Y_2 : Supplier On-time Rate (%)
Output (Z)	Z_1 : Return on Assess
	Z_2 : Rate of Accepted Products (%)
	Z_3 : Customer complaints (Number of registered per year)

Table 6.2 – Data sets of the samples

DMUs		X_1	X_2	X_3	Y_1	Y_2	Z_1	Z_2	Z_3
1	s1	7.49	306.90	42.50	96.63	93.23	0.36	98.53	17.00
	s2	8.21	271.30	42.50	97.14	96.20			
2	s1	4.46	271.30	42.50	96.49	92.23	0.66	96.92	15.00
	s2	12.05	306.90	42.50	96.93	95.30			
3	s1	6.58	306.90	40.00	95.00	91.88	1.23	98.62	13.00
	s2	12.06	282.80	40.00	97.12	96.00			
4	s1	7.67	271.30	43.00	96.00	91.09	2.33	97.65	9.00
	s2	13.40	271.30	45.00	97.62	94.20			
5	s1	4.97	373.80	47.00	96.56	91.83	2.72	97.08	1.00
	s2	14.11	373.80	45.00	96.97	95.20			
6	s1	5.20	282.80	42.50	96.40	91.68	3.41	97.18	18.00
	s2	16.51	306.90	47.00	98.22	95.60			
7	s1	6.00	373.80	45.00	96.62	91.59	3.46	97.74	8.00
	s2	20.37	271.30	42.50	97.69	94.00			
8	s1	5.24	282.80	42.50	96.04	91.79	3.97	97.31	16.00
	s2	21.03	373.80	42.50	97.39	94.90			

Table 6.3 reports the efficiency scores of non-contracted suppliers and supply

Table 6.3 – Efficiency results vs. customer complaints

DMUs	$\theta_{s2(o)}$	$\theta_{some(o)}$	customer complaints
1	0.999	0.973	17.00
2	0.949	1.000	15.00
3	1.000	1.000	13.00
4	1.000	1.000	9.00
5	0.888	0.904	23.00
6	0.902	0.989	18.00
7	1.000	0.936	8.00
8	0.944	0.995	16.00

chain obtained from the proposed model (model $some$). First, the efficiency score is analyzed then inefficient supply chains are focused with 'customer complaints' criterion. In the second column, we can find that replaceable suppliers of chain 1, 2, 5, 6, and 8 are inefficient. It means that only 3 suppliers are efficient among the 8 suppliers. On the other hand, we can see from the result that there are 4 chains that are inefficient among the 8 chains. The result shows that every inefficient replaceable suppliers are included in inefficient supply chains.

Now inefficiency chains with their 'customer complaints' criterion are considered. It is assumed that an efficient supply chain should provide a number of customers complaints as less as possible. As the above result of which there are 5 inefficient chains in this experiments, there are 4 chains which their efficiency scores and number customer complaints are the same as above assumption. This result can be explained that 'customer complaints' criterion is also one of important factors that affect chain efficiency. For instance, the most inefficient chain which is the fifth chain is brought in to be analyzed. In this chain, its customer complaints number is highest as 23 registered customer complaints. Besides, the fifth chain's replaceable supplier is the most inefficient suppliers among all replaceable suppliers as well.

The $\theta_{some(o)}$ shows an efficiency of chain in case that its replaceable supplier is inefficient and has not been. In the same way as the above example, the fifth chain which is the most inefficient chain is considered. I assume that only the fifth chain improves its replaceable supplier, a result in case that only the fifth chain improve comparing with other chain is shown in table 6.4.

In this table, results from the fifth chain are highlights. In third column, I assume that only fifth chain improves it suppliers, hence the fifth chain becomes efficient. As same as in the last column, the fifth chain is still efficient even all chains in a measurement improve their inefficient suppliers.

Table 6.4 – Efficiency score of the fifth chain

DMUs	No Improvement $\theta_{some(o)}$	Improve only fifth chain	All chains improve
1	0.973	0.987	0.998
2	1.000	1.000	1.000
3	1.000	1.000	1.000
4	1.000	1.000	1.000
5	0.904	1.000	1.000
6	0.989	0.989	1.000
7	0.936	0.983	0.989
8	0.995	0.985	1.000

As the above result, the proposed model is enabled to investigate replaceable suppliers efficiency with chain efficiency, and customer complaints while the tradition DEA models are not enable to do. Because in a measurement, efficiency scores of replaceable suppliers are included.

6.5 Conclusion

In this chapter, an efficiency of supply chain which focus on suppliers' side together with customer complaints has been investigated. The proposed DEA model described in Chapter 2, which considers constant and changeable suppliers concept has been utilized. As a case study, 4 inefficient chains among 8 chains have been found. In addition, the result shows that the most inefficient chain consists of both inefficient supplier and the highest number of customer complaints. From the result, we can conclude that an efficient supply chain should provide efficient supplier and less customer complaints. As the above result, the proposed model allows replaceable suppliers efficiency to be investigated with chain efficiency, and customer complaints while the tradition DEA models do not.

7 Conclusions and future directions

7.1 Conclusions

In this thesis, alternative models for supply chain efficiency measurement have been proposed under principle of DEA technique. The different types of suppliers, contracted and non-contracted suppliers, have been considered. The non-contracted suppliers are replaceable and others are irreplaceable due to their contract. Since that, efficiency scores of the non-contracted suppliers should be included in an efficiency measurement. Here, two situations are considered, all suppliers are non-contracted and can be replaced and some suppliers are non-contracted and they can be replaced. There are two models that are proposed in this research. The first model is for a situation in which all suppliers are non-contracted and the other is for a situation in which only some suppliers are non-contracted. The models have been introduced and mathematical proof is used to validate the proposed models.

To show an applicability of the proposed models, firstly, they have been tested with empirical data. Then the proposed models have been applied to case studies from the fields of frozen food supply chains in Thailand which includes two types of products, frozen shrimp and vegetable. These supply chains have two types of suppliers, contracted one and non-contracted one [19]. The results showed that numbers of inefficient supply chains from the two proposed DEA models are more than the numbers from the traditional DEA models. This presented that that the proposed models can identify inefficient supply chains more sensitively that the traditional ones. In practical part, the proposed models also provide an alternative target for inefficient supply chain to improve its inefficient suppliers. The applicability of the proposed models in which considering on customer satisfaction for situation that some suppliers of chain can be replaced and some does not is also shown.

7.2 Directions for future works

One extension of the proposed models in Chapter 3 is to measure an efficiency of a supply chain which consists non-contracted suppliers. In Chapter 4 and 5, an experiment of frozen food industry of Thailand and an application of the proposed models (model *some*) for investigating customers' satisfaction are demonstrated. To get efficiency score, MATLAB is used. In case that an organization want to measure its efficiency by using the proposed models, it may cause difficulties for general users. Therefore, developing of user friendly interface is expected in the future.

Besides, in the supply chain in which includes many suppliers which connect with contract of supply, two types of them are considered as contracted and non-contracted suppliers. In this research, this contract of supply concept is comprised by including suppliers' efficiency in the case that they are non-contracted suppliers. But for potential supply chain, only non-contracted suppliers' efficiency may not enough to represent the contract of supply between manufacturers and suppliers. Therefore, exploring more factors which are affected by contract of supply, e.g., information sharing level or condition of each supplier, and its effect on overall supply chain efficiency could be another direction for future work in this area.

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