How to evaluate sustainability of supply chains? A dynamic network DEA approach

Vahid Shokri Kahi

*Department of Management and Accounting, Karaj Branch,
Islamic Azad University, Karaj, Islamic Republic of Iran*

Saeed Yousefi

*Pegah Distribution Company,
Karaj, Islamic Republic of Iran*

Hadi Shabanpour

*Karaj Branch, Islamic Azad University,
Karaj, Islamic Republic of Iran, and*

Reza Farzipoor Saen

*Department of Industrial Management, Karaj Branch,
Islamic Azad University, Karaj, Islamic Republic of Iran*

Abstract

Purpose – The purpose of this paper is to develop a novel network and dynamic data envelopment analysis (DEA) model for evaluating sustainability of supply chains. In the proposed model, all links can be considered in calculation of efficiency score.

Design/methodology/approach – A dynamic DEA model to evaluate sustainable supply chains in which networks have series structure is proposed. Nature of free links is defined and subsequently applied in calculating relative efficiency of supply chains. An additive network DEA model is developed to evaluate sustainability of supply chains in several periods. A case study demonstrates applicability of proposed approach.

Findings – This paper assists managers to identify inefficient supply chains and take proper remedial actions for performance optimization. Besides, overall efficiency scores of supply chains have less fluctuation. By utilizing the proposed model and determining dual-role factors, managers can plan their supply chains properly and more accurately.

Research limitations/implications – In real world, managers face with big data. Therefore, we need to develop an approach to deal with big data.

Practical implications – The proposed model offers useful managerial implications along with means for managers to monitor and measure efficiency of their production processes. The proposed model can be applied in real world problems in which decision makers are faced with multi-stage processes such as supply chains, production systems, etc.

Originality/value – For the first time, the authors present additive model of network-dynamic DEA. For the first time, the authors outline the links in a way that carry-overs of networks are connected in different periods and not in different stages.

Keywords Data envelopment analysis, Sustainable supply chain management, Efficiency evaluation, Food supply chain, Dynamic DEA, Network DEA, Slacks-based measure

Paper type Research paper

1. Introduction

Supply chain is a purposeful combination of interconnected and interdependent organization. Although, units of supply chains are separated legally, they are connected by flow of material, information, and finance. Providing the best combination of resources via outsourcing is the main issue of supply chain management (SCM) in modern business enterprises (Ageron *et al.*, 2012). Price, quality, flexibility, and supplier reputation are economic criteria in SCM evaluation (Bai and Sarkis, 2010).

Nowadays, sustainability factors play a critical role in long-term achievement of SCM; accordingly, purchasing process becomes more complicated with social and environmental pressures. As Govindan *et al.* (2013) addressed, over the past decades, due to rapid reduction of natural resources, concerns over wealth inequality and corporate social responsibility, sustainability has become important for researchers and scholars. In other words, there are pressures which force SCM to focus not only on economic but also on social and environmental criteria (Dyllick and Hockerts, 2002). Thus, sustainable supply chain may be of great importance attributable to surging environmental conservation and societal prosperity while reinforcing economic intention of organization. To do so, companies should conserve resources, optimize processes, uncover product innovations, save costs, increase productivity and promote corporate values by managing and improving environmental, social, and economic performances across supply chains (Seuring and Müller, 2008). On the other hand, there are several sustainability criteria which complicate SCM's evaluation. This means that decision-makers encounter some discretionary/free and even contradictory criteria while evaluating sustainability of SCM. Dual-role links, inputs, desirable and undesirable outputs are some of the main criteria.

In an accurate appraisal of supply chain, interactions among suppliers should be taken into consideration. To evaluate sustainability of SCM, dealing with multiple criteria has been one of the significant concerns in preceding models (Yousefi *et al.*, 2016). To deal with multiple criteria, this paper develops a novel network-dynamic data envelopment analysis (DEA) model. Wong *et al.* developed two DEA models including technical efficiency and cost efficiency models to explain application of DEA in measuring supply chain performance. Traditional DEA models measure relative efficiency of decision-making units (DMUs) (Charnes *et al.*, 1978; Tavassoli *et al.*, 2014).

However, one of the most growing criticisms in these sorts of models is that the DMUs are assessed in a specific period. Given fluctuations in performance of DMUs during several periods, considering just a specific period is insufficient in comprehensive efficiency evaluation. In dynamic DEA presented by Tone and Tsutsui (2010), the DMUs' efficiencies are assessed during several periods. However, dynamic DEA does not deal with DMUs' internal structures. Network DEA (NDEA) deals with DMUs with internal structures (Yu and Lin, 2008). Tone and Tsutsui (2014) proposed network-dynamic DEA model in which the DMUs were assessed in multiple periods with internal interactions. Their model is based upon slack-based measure (SBM) model.

Objective of this paper is to improve the dynamic DEA model proposed by Tone and Tsutsui (2014). To this end, we develop a novel dynamic DEA model with network structure in which, for the first time, the overall carry-overs of a network in period (*t*) enter next period (*t*+1). Note that Tone and Tsutsui (2014) connected multiple stages in different periods. In Tone and Tsutsui (2014), the carry-overs of each stage inside period (*t*) enter the next period (*t*+1) separately and independently. However, in our proposed approach, the overall values of carry-overs for each network are obtained and enter the next period. In other words, Tone and Tsutsui (2014) connected the stages to each other (among periods) but we connect each network (as a whole) to other networks. Hence, as it is shown in Figure 1, we consider each period (*t*) as a network which enters next period (*t*+1) by carry-overs. Here, in addition, free links among periods are defined in terms of desirable and undesirable carry-overs. Figure 1 displays our novel network dynamic DEA structure. Note that all notations in Figure 1 are defined in Section 3.

Despite Tone and Tsutsui (2014), our proposed approach has following advantages: our approach connects the periods by networks' carry-overs and not stages' carry-overs; we define nature of free links and apply them in calculating relative efficiency of supply chains (DMUs); we develop an additive NDEA model for evaluating sustainability of supply chains in several periods.

There are numerous criticisms directed at the model proposed by Tone and Tsutsui (2014). In the aforementioned model multiple networks are simultaneously introduced as efficient units; therefore, the model fails in ranking the supply chains (DMUs). Second, the types of link among periods have dominant weakness. Changing an inefficient period to efficient period by the solution suggested by Tone and Tsutsui (2014), causes other periods to become inefficient. In other words, by increasing output of a period, inputs of next periods will be increased. This causes inefficiency of next periods. This happens due to poor definition of links in Tone and Tsutsui (2014) model. To address this weakness, we use different method. Besides, in our model the links among networks in periods are connected in an integrated way.

It is noteworthy that Tone and Tsutsui (2014) did not determine nature of the free links and also ignored the free links in calculation of DMUs' efficiency. In other words, in the approach proposed by Tone and Tsutsui (2014), decision maker cannot identify whether a free link is a desirable or undesirable factor. Note that a free link connects two periods and consists of desirable and undesirable types (Yousefi *et al.*, 2016). Tone and Tsutsui (2014) did not clarify nature of free links. Hence, in this paper not only do we define the nature of free links but we also use all the links in assessing sustainability of supply chains (DMUs). In this paper, the links are classified into three categories, i.e. desirable, undesirable and free links which join multiple periods in series form. Note that our proposed network-dynamic DEA model is based upon additive model in which both networks and links have series structure and each period is a network.

Next sections of the paper are as follows: Literature review is presented in Section 2. In Section 3, proposed model is given. Case study is discussed in Section 4. Obtained results and concluding remarks are presented in Section 5. In Section 5.2, managerial implications are given.

2. Literature review
2.1 DEA and sustainable supply chain evaluation
Organizations are responsible for their environmental and social performance (Zhu *et al.*, 2005). Sustainable development emphasizes on environment, economy, and society. Evaluating sustainable supply chain management (SSCM) performance is a key challenge (Tseng *et al.*, 2015). SSCM has turned out to be a strategic process which enables firms to create competitive advantage. Customers' demands and products' complexity have increased competition among organizations. SSCM provides an opportunity for organizations to distinguish itself from its competitors. Thus, it provides a competitive advantage in market (Khodakarami *et al.*, 2015). Numerous organizations have already commenced to develop a certain level of commitment toward sustainability practices to make their supply chains
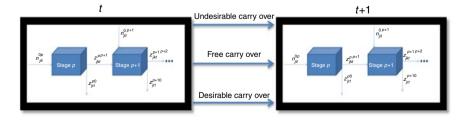

Figure 1.
Typical structure of dynamic model with network structure

sustainable (Govindan *et al.*, 2015). SSCM evaluation, hence, is a substantial duty for any types of organizations. Among evaluation methods, DEA appears to be a suitable technique to assess SSCM.

DEA measures relative efficiency of DMUs (Charnes *et al.*, 1978). DEA has been used in assessing supply chains (Liang *et al.*, 2006). To measure efficiency of supply chains, Chen *et al.* (2006) developed a DEA-game model. Yu *et al.* (2010) assessed efficiency of supply chains by cross-efficiency DEA model without considering internal structure of supply chains. To measure performance of supply chains, Wong and Wong (2007) determined technical efficiency and cost efficiency of supply chains. Wong *et al.* (2008) developed a method for assessing efficiency of supply chains by stochastic DEA model. One of the DEA applications is to evaluate efficiency of two-stage processes where all outputs of the first stage are intermediate measures which are considered as inputs of the second stage. As a result, two-stage DEA models assess both overall efficiency score of whole process and each of the individual stages (Khodakarami *et al.*, 2015). DEA, furthermore, has been used to evaluate environmental and social performance of various settings (Sueyoshi and Goto, 2010; Noorizadeh *et al.*, 2011; Rashidi *et al.*, 2015; Azadi *et al.*, 2015). Sueyoshi and Goto (2010) used DEA to assess effectiveness of US clean air act in controlling CO_2 emission. Rashidi *et al.* (2015) applied DEA to estimate energy saving and undesirable output abatement of 25 countries. To assess sustainability of supply chains, Wu *et al.* (2016) provided both theoretical and quantitative tool.

Nevertheless, as previously mentioned, in classical models of DEA internal interactions are neglected. Given that sustainable supply chains encompass a complex network of connections and interactions, traditional DEA models have been evolved to overcome the shortcomings.

2.2 NDEA and dynamic DEA

To evaluate efficiency of a DMU, Färe and Grosskopf (1996, 2000) proposed an NDEA model with multiple production stages. Over the last decade, a couple of radial NDEA models have been presented (e.g. Lewis and Sexton, 2004; Färe *et al.*, 2007; Kao and Hwang, 2010; Cook *et al.*, 2010). Lewis and Sexton (2004) applied an NDEA model to evaluate organizational efficiency of companies with complex internal structure. Kao and Hwang (2010) utilized NDEA to measure efficiency of network systems taking into account IT impact on firm performance. Färe *et al.* (2007) developed an NDEA model by modeling data structures irregularities and structural complexities in DEA. Cook *et al.* (2010) selected the best supply chains by NDEA model. Liang *et al.* (2006) developed a non-linear model to determine efficiency of supply chains and their members. Chen and Yan (2011) presented a radial NDEA model to measure efficiency of supply chains. Yousefi *et al.* (2015) developed an NDEA model by goal programming to select the best supply chains.

For the first time, Sengupta (1995) introduced dynamic DEA model (D-DEA) and later it was extended based on the studies of Färe and Grosskopf (1996). They proposed a dynamic production frontier using an intermediate output which relates annual production processes. However, developing a new dynamic slacks-based measure (DSBM) model by Tone and Tsutsui (2010) was a turning point in the D-DEA literature. They suggested four types of carry-overs (links); desirable, undesirable, discretionary, and non-discretionary (fixed) links to assess DMUs in different periods. The paper proposed by Tone and Tsutsui (2014) may be considered as one of the most comprehensive and reliable methods to evaluate sustainability of supply chains. They, for the first time, merged network SBM and DSBM models. By so doing, they proposed a dynamic DEA model with network structure. However, they did not specify some important items in their model.

2.3 The proposed approach's necessity

In traditional DEA models as well as current dynamic DEA models, internal processes within the DMUs are not considered. In a comprehensive and realistic assessment of DMUs (networks), internal structures should be assessed. This means that all links among and inside the DMUs (networks) should be appropriately considered and defined. Unlike the real world, Tone and Tsutsui (2014) applied stages as periods and not networks and they ignored to explicitly define nature of free links in their model. In other words, they overlooked to determine whether free links are desirable or undesirable. Hence, they ignored to employ free links in calculating efficiency of DMUs.

This paper intends to address these gaps. Indeed, very few papers so far have considered all the aforementioned criteria along with sustainability in supply chain using an optimization approach. For the first time, in this paper, a network-dynamic DEA model is proposed which is able to assess sustainability of supply chains in different periods. It should be mentioned that the connections among periods are as the links among networks and not stages. Besides, this model can assess sustainability of supply chains in multiple periods using additive model of network-dynamic DEA. In summary, contributions of this paper are as follows.

- for the first time, we present additive model of network-dynamic DEA;

- we develop temporal link among networks based on series view;

- we utilize the free links and determine their nature; and

- for the first time, we outline the links in a way that carry-overs of networks are connected in different periods and not in different stages.

3. Proposed method

3.1 Algorithm

To introduce our proposed method, following steps are taken: In step 1, we provide data set as inputs, outputs, and links for each supply chain. In step 2, our dynamic NDEA model is run to evaluate sustainability of supply chains. In step 3, rank of supply chains is determined and the best sustainable supply chain is introduced. These steps are presented in Figure 2.

3.2 Definition of variables, network structure of supply chains, and dynamic DEA
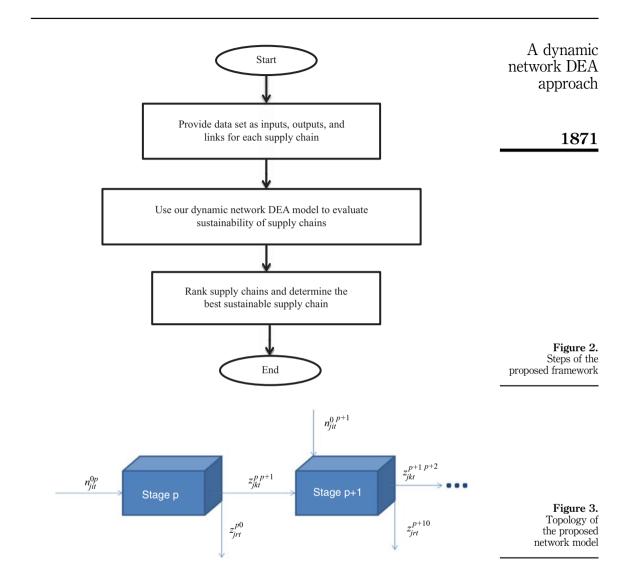
At this juncture, as is shown in Figure 3, the network model is defined. Here, n_{jit}^{0p} represents ith input ($i = 1, …, I$) of jth DMU ($j = 1, …, m$) in tth period ($t = 1, …, T$) which feeds stage p from outside. z_{jkt}^{pp+1} indicates kth output ($k = 1, …, K$) of jth DMU ($j = 1, …, m$) in tth period ($t = 1, …, T$) as output of stage p ($p = 1, …, P$) which feeds stage $p+1$ as input. z_{jrt}^{p0} signifies rth output ($r = 1, …, s$) of jth DMU ($j = 1, …, m$) in tth period ($t = 1, …, T$) as output of stage p ($p = 1, …, P$) which exits from network.

The relevant multipliers (weights) of the above factors are defined as follows:

- λ_{pr}: multiplier of the output z_{jrt}^{p0} exiting from stage p.

- β_{pk}: multiplier of the output z_{jkt}^{pp+1} which exits the stage p and enters stage $p+1$.

- α_{pi}: multiplier of the input $n_{jit}^{0\,p}$ entering the network at beginning of stage p from outside.

Now, the efficiency of stage 1 in tth period is defined as follows. It should be noted that the first stage is the only stage in which all inputs enter the network from outside and not from prior stage:

$$\rho_{1j} = \frac{\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{1\,0} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{1\,2}}{\sum_{i=1}^{I} \alpha_{pi} n_{jit}^{0\,1}} \tag{1}$$

Figure 2.
Steps of the
proposed framework

Figure 3.
Topology of
the proposed
network model

Numerator of Equation (1) expresses two terms, weighted sum of outputs that exit the
network as final output and also weighted sum of output which exits from the first stage and
enters the second stage as input. Besides, denominator indicates weighted sum of inputs that
enter stage 1 from outside. Efficiencies of other stages are defined by the following equation.
Other stages can possess two types of inputs; that is inputs which enter the stage from outside
and also the inputs that are outputs of prior stage and enter the stage p as input:

$$\rho_{pj} = \frac{\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12}}{\sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{jit}^{01}} \tag{2}$$

Numerator of Equation (2) expresses the weighted sum of outputs which exit the network as
final output and also weighted sum of outputs that exit the stage p and enter the stage $p+1$.

Denominator indicates weighted sum of inputs that enter stage $p+1$ directly from stage p and weighted sum of inputs which enter the stage p from outside of network.

Now, overall efficiency of jth DMU is defined in the following equation:

$$P_j = \frac{\sum_{p=1}^{P} \left(\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} \right)}{\sum_{p=1}^{P} \left(\sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{jit}^{01} \right)} \tag{3}$$

Equation (3) indicates the overall efficiency of network. Numerator of Equation (3) expresses weighted sum of all outputs including the outputs which exit the network as final outputs; and the outputs which exit stage p but enter stage $p+1$ as input. Denominator indicates all inputs including inputs which go into stage $p+1$ after they leave stage p; and the inputs which enter the stage p from outside of network.

3.3 Proposed dynamic DEA model's structure

At this juncture, we represent our proposed dynamic DEA model which evaluates the supply chains in which the networks have series structure. As depicted in Figure 1, we classify the links into three categories. Thus, we define desirable (good) link, undesirable (bad) link, and free link (dual-role link) as typical carry-overs among periods. Let us now define following links:

(1) Desirable (good) link: this link indicates desirable carry-over which connects tth period to $t+1$ period. In our model, we maximize this kind of link.

(2) Undesirable (bad) link: this link corresponds to undesirable carry-over which connects tth period to $t+1$ period. In our model, we minimize this kind of link.

(3) Free (discretionary) link: free link signifies discretionary carry-over which connects tth period to $t+1$ period. This type of link has dual-role nature. This means that free link can be stated desirable or undesirable. One of the results of the model presented in this paper is that it defines nature of this type of link.

Now, factors and their weights are defined as follows:

- c_{jlt}^{free} ($l = 1, \ldots, L$ free) displays free link of jth DMU in tth period ($t = 1, \ldots, T$) which enters into period $t+1$.

- c_{jlt}^{d} ($1 = 1, \ldots, L\ d$) indicates desirable (good) link of jth DMU in tth period ($t = 1, \ldots, T$) which connects to period $t+1$.

- c_{jlt}^{und} ($1 = 1, \ldots, L$ und) shows undesirable (bad) link of jth DMU in tth period ($t = 1, \ldots, T$) which enters into period $t+1$.

- ϑ_{tl} is multiplier of desirable carry-over related to the free link c_{jlt}^{free} indicating degree of desirability in free link.

- ω_{tl} is multiplier of undesirable carry-over related to the free link c_{jlt}^{free} indicating degree of undesirability in free link.

- γ_{tl} is multiplier of desirable link c_{jlt}^{d}.

- ν_{tl} is multiplier of undesirable link c_{jlt}^{und}.

Given the above discussions, overall efficiency of jth network under evaluation in tth period is defined as following objective function:

$$\phi_j^t = \frac{\sum_{l=1}^{L} \gamma_{tl} c_{jlt}^d + \sum_{l=1}^{L} \vartheta_{tl} c_{jlt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} \right)}{\sum_{l=1}^{L} v_{tl} c_{jlt}^{\text{und}} + \sum_{l=1}^{L} \omega_{tl} c_{jlt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{jit}^{01} \right)} \tag{4}$$

Equation (4) represents jth network's efficiency ratio. In this equation, weighted values of the link are taken into account which connects the period t to period $t+1$ in jth network. We can distinguish Φ_j^t as two merged fractions consisting of the fraction in the second part indicating P_j (Equation (3)) in which both numerator and denominator have parentheses and fraction without parentheses in the first part of Equation (4) which demonstrates weighted ratio of desirable links to undesirable ones. We wish to determine free links' nature in terms of being desirable or undesirable. Accordingly, we introduce the links with two multipliers. Each of these multipliers indicates whether the free links are desirable or undesirable factors. Here, we set sum of these multipliers to 1 in which multipliers signify degree of desirability or undesirability of free links:

$$v_{tl} + \omega_{tl} = 1 \tag{5}$$

Hence, in general, ratio of links for networks in different periods is defined as follows:

$$\phi = \frac{\sum_{l=1}^{L} \gamma_{tl} c_{jlt}^d + \sum_{l=1}^{L} \vartheta_{tl} c_{jlt}^{\text{free}}}{\sum_{l=1}^{L} v_{tl} c_{jlt}^{\text{und}} + \sum_{l=1}^{L} \omega_{tl} c_{jlt}^{\text{free}}} \tag{6}$$

To optimize overall efficiency Φ, a multi-stage process is needed as restrictions ρ_{pj}, ρ_1, and ϕ should not be more than 1. At this juncture, given definitions and formulas, overall non-linear model is presented as follows:

$$\text{Max} \quad \frac{\sum_{l=1}^{L} \gamma_{tl} c_{jlt}^d + \sum_{l=1}^{L} \vartheta_{tl} c_{jlt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} \right)}{\sum_{l=1}^{L} v_{tl} c_{jlt}^{\text{und}} + \sum_{l=1}^{L} \omega_{tl} c_{jlt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{jit}^{01} \right)}$$

s.t.:

$$\frac{\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12}}{\sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{jit}^{01}} \geqslant 1 \tag{7}$$

$$\frac{\sum_{l=1}^{L} \gamma_{tl} c_{jlt}^d + \sum_{l=1}^{L} \vartheta_{tl} c_{jlt}^{\text{free}}}{\sum_{l=1}^{L} v_{tl} c_{jlt}^{\text{und}} + \sum_{l=1}^{L} \omega_{tl} c_{jlt}^{\text{free}}} \geqslant 1$$

$$\vartheta_{tl} + \varpi_{tl} = 1$$

$$\gamma_{tl} \geqslant 0, \vartheta_{tl} \geqslant 0, \lambda_{pr} \geqslant 0, \beta_{pk} \geqslant 0, v_{tl} \geqslant 0, \omega_{tl} \geqslant 0, \alpha_{pi} \geqslant 0.$$

Formulas (2), (4), (5), and (6) are incorporated into model (7). Non-linear model (7) includes formula (4) in the objective function. Formula (2) is used as the first constraint and formula (5) and (6) are applied in second constraint. Model (7) is a non-linear model which should be converted to a linear model. Charnes-Cooper approach may be utilized to convert the

non-linear models to linear models (Charnes *et al.*, 1978). The *o* in our proposed model (8) implies the DMU under evaluation:

$$\text{Max} \sum_{l=1}^{L} \gamma_{tl} c_{olt}^{d} + \sum_{l=1}^{L} \vartheta_{tl} c_{olt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{r=1}^{s} \lambda_{pr} z_{ort}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{okt}^{12} \right)$$

s.t.:

$$\sum_{l=1}^{L} v_{tl} c_{olt}^{\text{und}} + \sum_{l=1}^{L} \varpi_{tl} c_{olt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{k=1}^{K} \beta_{pk} z_{okt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{oit}^{01} \right) = 1$$

$$\sum_{l=1}^{L} v_{tl} c_{olt}^{\text{und}} + \sum_{l=1}^{L} \varpi_{tl} c_{olt}^{\text{free}} + \sum_{p=1}^{P} \left(\sum_{k=1}^{K} \beta_{pk} z_{okt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{oit}^{01} \right) = 1 \qquad (8)$$

$$\sum_{r=1}^{s} \lambda_{pr} z_{jrt}^{10} + \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} \leqslant \sum_{k=1}^{K} \beta_{pk} z_{jkt}^{12} + \sum_{i=1}^{I} \alpha_{pi} n_{jit}^{01}$$

$$\sum_{l=1}^{L} \gamma_{tl} c_{jlt}^{d} + \sum_{l=1}^{L} \vartheta_{tl} c_{jlt}^{\text{free}} \leqslant \sum_{l=1}^{L} v_{tl} c_{jlt}^{\text{und}} + \sum_{l=1}^{L} \omega_{tl} c_{jlt}^{\text{free}}$$

$$\vartheta_{tl} + \varpi_{tl} = 1$$

$$\gamma_{tl} \geqslant 0, \vartheta_{tl} \geqslant 0, \lambda_{pr} \geqslant 0, \beta_{pk} \geqslant 0, v_{tl} \geqslant 0, \omega_{tl} \geqslant 0, \alpha_{pi} \geqslant 0.$$

The objective function in model (8) indicates DMU's efficiency score in the period under evaluation. Furthermore, to illustrate weighted average of network efficiency during several periods, so the following expression is presented:

$$\Phi_j = \sum_{t=1}^{T} w^t \phi_j^t \Phi_j = \sum_{t=1}^{T} w^t \phi_j^t \qquad (9)$$

$$\sum_{t=1}^{T} w^t = 1$$

In next section, a case study is given.

4. Case study

Delpazir Company is a private holding company in food industry which was established in 1980 in Iran. The company's main products include tomato paste and tomato sauce. Delpazir Company has 17 branches in different provinces of Iran. Each branch has a separate supply chain which produces tomato paste. The supply chains are assessed and controlled under supervision of Delpazir Company holding. Delpazir group has the most advanced and up-to-date food processing factories across the Middle East enjoying the

most advanced European machinery with top technology in food industry. Delpazir group is comprised of three major sectors as follows:

(1) Kadbanoo Co. with more than 61 years of experience in food industry does the production and outsourcing of Delpazir products encompassing more than 50 stock keeping units including mayonnaise and salad dressings, canned food, tea, tomato paste, and ketchup.

(2) Imports and exports are executed by Akam Co. Akam exports various products to neighbor countries.

(3) Sales and distribution is performed by Pegah Co. With 29 years of experience, Pegah Co. is operating with more than 150 SKU's and 4 major brands in fast moving consumer goods industry. Pakhsh Pegah was established in 1983 and is responsible for distribution, sales and marketing of domestic and foreign products across Iran. This company distributes products through 14 distribution centers across Iran and has always been a pioneer in distribution industry.

In this paper, sustainability of 17 supply chains is assessed during 2012 to 2014. To assess sustainability of supply chains, economic, environmental, and social factors are taken into account. Each supply chain has three stages including farms, canning factories, and chain stores. Inputs and outputs of supply chains given three stages are defined below:

(1) Inputs and outputs of farms:

- Inputs:
  – Environmental costs ($1,000) as an environmental criterion which represents amount of money that is paid for environmental damage in a year.
  – Cost of labor safety ($1,000) as a social criterion which represents amount of money that is for compensating labor damages in a year.
  – Other costs (economic criterion).

- Outputs:
  – Revenue from sales of tomatoes as raw material which are sent to tomato-paste factory ($1,000) as an economic criterion.
  – Revenue from sales of raw tomatoes in markets ($1,000) as the other economic criterion.

(2) Inputs and outputs of canning factories:

- Inputs:
  – Cost of purchasing tomato from farm ($1,000) as an economic criterion.
  – Environmental costs ($1,000) as an environmental criterion which is amount of money that is paid for environmental damage in a year.
  – Cost of labor safety ($1,000) as a social criterion which is amount of money that is paid for compensating labor damage in a year.

- Outputs:
  – Volume of tomato pastes which are ready for sales (economic criterion) in a year.

(3) Inputs and outputs of chain stores:

- Inputs:
  – Volume of tomato pastes which are ready for sales (economic criterion) in a year.
  – Shipping costs ($1,000) as an economic criterion.

– Cost of labor safety ($1,000) as a social criterion which represents amount of
money that is paid for compensating labor damage during a year.

- Outputs:

– Annual profit ($1,000) as an economic criterion.

Degree of customer satisfaction (as a social criterion) which is measured by nine-point Likert
scale. Table I shows Likert scale (Likert, 1932). Delpazir Co. utilizes opinions of customers to
measure customer satisfaction.

Given the aforementioned definitions of inputs, outputs, and links, structure of supply
chains is displayed in Figure 4.

Furthermore, as is shown in Figure 5, each period has three links to next period which
are as follows:

(1) Not collected revenue (desirable link).

(2) Unpaid costs (undesirable link).

(3) Green research and development (green R&D) (free/dual-role link). In Delpazir
Company, green R&D costs are paid for elimination of chemical and non-organic
processes from tomato supply chain.

Historical data of 17 supply chains from 2012 to 2014 are reported in Table II. The data set is
obtained through recorded documents of Delpazir Company as well as the company's
executives. Note that there are 17 supply chains of Delpazir Company in 17 provinces of Iran.
They operate separately and independently while being directed by a central ownership.

Value	Customer satisfaction
9	High satisfaction
7	Good satisfaction
5	Medium satisfaction
3	Low satisfaction
1	Very low satisfaction
2-4-6-8	Intermediate factors

Table I.
Likert scale for
measuring customer
satisfaction
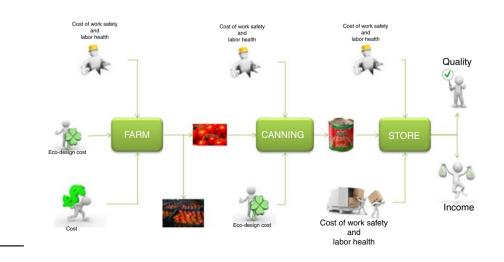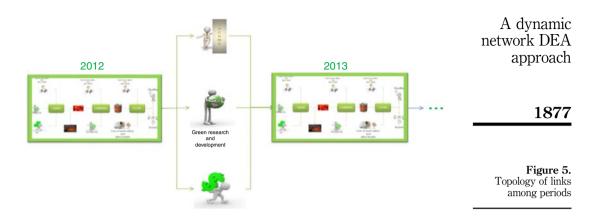
Figure 4.
Structure of
supply chains

Green research
and
development

Figure 5.
Topology of links
among periods

By running model (7), the supply chains are assessed over three years. Efficiency scores of 17 supply chains in three years are shown in Table III. Besides, nature of the dual-role links is identified in all supply chains.

According to Table III, if the ϑ becomes 1, the dual-role link has desirable nature. If the ϖ becomes 1, the link has undesirable nature. However, some sustainable supply chains may seem superior due to excellent efficiency scores only in a specific period. For example, in 2013, supply chains 15 and 16 are more sustainable than other supply chains. But, given overall efficiency, they are ranked as 7th and 8th, respectively. Though supply chains 17, 13, 9, and 4 are not sustainable in any period, they have received a better rank compared with supply chains 15 and 16. Given overall efficiency, the supply chain 5 is the most sustainable supply chain during all periods.

5. Conclusions

5.1 Obtained results

The traditional DEA models do not explicitly ascertain any of key sub-processes involved in divisions of supply chains. Furthermore, one of the drawbacks of these models is oversight of internal structure of supply chains (DMUs). As an illustration, numerous companies embrace several divisions that are linked to each other having division-specific inputs and outputs along with links to other divisions. It is recognized that supply chains (DMUs) may have multi-stage structures where initial stage utilizes inputs to produce outputs that become inputs of the second stage and the second stage employs the first stage outputs to produce its own outputs. On the other hand, there exist several sustainability criteria complicating SCM's evaluation. Accordingly, these make decision-makers encounter some discretionary/free and even contradictory criteria while evaluating sustainability of SCM. Dual-role links, inputs, desirable and undesirable outputs are some of main criteria.

To deal with multiple criteria, we proposed a novel method to consider interactions among supply chains and overall efficiencies in network-dynamic DEA. This enables decision makers not only to acquire the overall efficiency of supply chains (DMUs) over entire periods, but also to observe dynamic change of period efficiency and dynamic change of divisional efficiency of DMUs. Our approach excellently overcomes deficiencies of previous methods. We have also extended and improved Tone and Tsutsui (2014) dynamic DEA model. In our proposed approach, overall values of carry-overs for each network are obtained and afterwards are entered to succeeding period. In other words, Tone and Tsutsui (2014) connected the stages to each other (among periods) but we connect each network (as a whole) to other networks. Here, in addition, free links among periods are defined in terms of desirable and undesirable carry-overs. Numerical illustrations have been provided in a case study to demonstrate

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2012																	
Farm																	
Inputs																	
Labors' safety cost	15	19	35	15	9	12	15	14	16	20	14	19	30	32	19	24	22
Environmental costs	29	24	34	20	15	20	28	33	26	28	30	36	23	18	26	20	34
Other costs	44	43	45	28	20	28	37	36	40	40	41	46	42	39	40	5	41
Outputs																	
Revenue from tomato sales to factories	730	790	740	890	990	890	700	720	790	850	740	810	720	830	840	880	780
Revenue from tomato sales in markets	19	21	28	26	555	20	23	23	24	25	19	20	21	26	24	23	22
Canning factories																	
Inputs																	
Received tomato from farm	730	790	740	890	990	890	700	720	790	850	740	810	720	830	840	880	780
Environmental costs	24	26	36	23	12	20	26	25	23	29	28	21	30	26	29	24	23
Labors' safety cost	19	21	11	14	9	18	15	20	18	16	20	21	25	14	12	17	16
Shipping cost	16	21	28	16	9	15	12	15	10	14	13	18	31	12	24	15	23
Outputs																	
Tomato pastes ready to use	208,500	225,200	200,500	231,000	285,300	223,800	212,400	202,600	206,500	215,600	209,600	210,500	202,100	207,000	226,900	225,400	217,800
Chain stores																	
Inputs																	
Tomato pastes ready to use	208,500	225,200	200,500	231,000	285,300	223,800	212,400	202,600	206,500	215,600	209,600	210,500	202,100	207,000	226,900	225,400	217,800
Shipping cost	20	19	31	25	5	16	14	14	15	16	10	13	30	16	14	12	19
Labor cost	37	34	29	35	15	39	34	23	29	28	30	40	45	38	36	29	34
Outputs																	
Revenue	16,400	12,100	11,800	11,900	21,500	12,800	14,200	13,100	11,000	12,400	12,300	10,900	11,200	11,600	10,900	12,400	11,500
Degree of customer satisfaction	7	7	6	7	9	7	8	7	8	8	8	8	7	7	7	8	7
Links																	
Unpaid costs																	
Undesirable link	420	390	340	360	290	340	480	490	430	480	460	510	520	450	490	340	360
Not collected revenues																	

(continued)

Table II.
Inputs, outputs, and links of three years

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Desirable link	460	510	490	590	705	610	550	490	580	430	450	530	260	690	490	5,500	690
Green R&D																	
Dual-role link	430	410	500	490	420	390	310	340	360	420	460	420	390	350	460	360	410
2013																	
Farm																	
Inputs																	
Labors safety cost	23	27	21	27	24	38	24	22	20	24	29	21	19	30	24	15	12
Environmental costs	36	22	30	31	30	45	28	24	25	33	28	28	20	31	23	20	16
Other costs	54	48	50	55	48	69	41	52	44	50	54	41	42	53	51	33	29
Outputs																	
Revenue of tomato sales to tomato-paste factories	820	810	780	880	800	580	750	770	820	810	820	800	820	750	880	910	990
Revenue of fresh tomato sales to external markets	31	34	21	35	25	14	20	23	32	33	30	34	23	34	31	46	55
Canning factories																	
Inputs																	
Received tomato (purchasing tomato from farm)	820	810	780	880	800	580	750	770	820	810	820	800	820	750	880	910	990
Environmental costs	28	32	26	14	25	47	26	27	36	20	21	23	29	29	21	10	12
Employees safety cost	23	20	21	20	25	40	26	28	20	21	27	23	21	24	29	9	14
Shipping cost	20	14	21	10	24	36	15	20	23	23	14	15	10	17	18	5	8
Outputs																	
Tomato pastes ready to use	200,900	206,900	223,600	222,000	203,100	203,800	208,800	205,000	206,900	207,300	203,200	204,900	219,900	204,400	203,700	245,200	237,400
Chain stores																	
Inputs																	
Tomato pastes ready to use	200,900	206,900	223,600	222,000	203,100	203,800	208,800	205,000	206,900	207,300	203,200	204,900	219,900	204,400	203,700	245,200	237,400
Shipping cost	22	29	23	12	21	27	27	26	24	24	24	21	23	24	22	8	10
Labor force cost	31	34	27	20	30	30	30	36	32	36	34	36	39	32	35	14	16
Outputs																	
Revenue	12,100	13,000	13,500	13,500	12,500	10,100	11,500	11,800	12,900	13,300	11,800	12,200	13,000	13,300	13,000	23,000	22,300

(continued)

A dynamic network DEA approach

1879

Table II.

Table II.

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Degree of customer satisfaction	7	8	7	9	7	7	7	7	8	7	8	7	8	7	9	9	9
Links																	
Unpaid costs																	
Undesirable link	510	420	450	360	470	470	490	520	400	490	410	490	440	500	480	220	250
Not collected revenues																	
Desirable link	590	580	730	770	610	630	590	650	680	560	695	710	700	840	650	810	850
Green R&D																	
Dual-role link	450	580	510	560	440	410	510	510	470	510	440	480	530	540	490	410	510
2014																	
Farm																	
Inputs																	
Employees safety cost	21	18	30	24	21	23	11	28	21	19	19	15	24	29	36	16	18
Environmental costs	22	23	28	32	31	35	12	42	20	36	23	30	26	33	21	36	33
Other costs	43	49	49	47	54	45	20	67	44	42	43	53	49	55	45	51	40
Outputs																	
Revenue of tomato sales to tomato-paste factories	770	830	950	850	820	820	990	830	800	820	940	930	800	800	780	860	830
Revenue of fresh tomato sales to external markets	23	23	28	25	32	21	28	35	33	25	30	23	35	21	14	23	28
Canning factories																	
Inputs																	
Received tomato (purchasing tomato from farm)	770	830	950	850	820	820	990	830	800	820	940	930	800	800	780	860	830
Environmental costs	34	28	30	26	29	29	11	36	25	32	35	34	23	14	41	23	22
Employees safety cost	21	25	15	16	25	23	16	39	29	25	28	29	28	15	37	15	21
Shipping cost	21	22	22	24	12	24	11	29	22	28	22	22	26	21	32	20	18
Outputs																	
Tomato pastes ready to use	214,300	209,300	202,700	206,100	229,500	203,500	248,900	205,800	200,300	205,800	206,000	202,400	203,700	223,500	209,000	202,500	204,200

(continued)

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Chain stores																	
Inputs																	
Tomato pastes ready to use	214,300	209,300	202,700	206,100	229,500	203,500	248,900	205,800	200,300	205,800	206,000	202,400	203,700	223,500	209,000	202,500	204,200
Shipping cost	18	18	18	15	10	19	9	32	21	22	15	23	25	10	32	21	15
Labor force cost	29	27	25	23	13	28	15	33	28	26	29	26	26	21	47	29	23
Outputs																	
Revenue	11,900	11,000	11,500	11,200	12,700	14,200	13,600	10,400	10,300	10,600	11,600	10,000	11,700	10,500	10,100	11,600	11,700
Degree of customer satisfaction	7	7	8	8	9	7	9	7	8	7	8	7	7	9	6	7	8

Table II.

Table III.
Efficiency scores of 17 supply chains in three years

Supply chains	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2012																	
Efficiency scores	0.67	0.59	0.49	0.93	1	0.93	0.85	0.82	0.68	0.65	0.59	0.45	0.89	0.84	0.92	0.69	0.87
ϑ	0	0	0	1	1	1	1	1	0	0	0	0	1	1	1	0	1
ϖ	1	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0
2013																	
Efficiency scores	0.84	0.71	0.82	0.96	0.91	0.54	0.94	0.66	0.88	0.75	0.9	0.81	0.82	0.91	1	1	0.94
ϑ	1	0	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1
ϖ	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
2014																	
Efficiency scores	0.84	0.75	0.72	0.83	0.93	0.69	1	0.52	0.98	0.63	0.87	0.88	0.95	0.47	0.61	0.74	0.92
Overall efficiency	0.78	0.683	0.676	0.906	0.95	0.72	0.93	0.67	0.85	0.68	0.79	0.71	0.89	0.74	0.84	0.81	0.91
Rank	10	14	16	4	1	12	2	17	6	15	9	13	5	11	7	8	3

applicability of the proposed approach. We examined performance of seventeen supply chains of Delpazir Company in 17 provinces of Iran in 2012-2014.
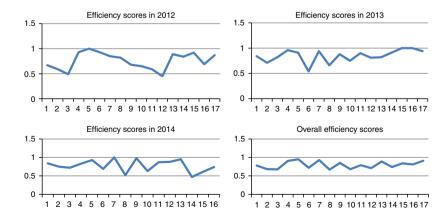
Case study was run to evaluate performance of supply chains in several periods. Results of analysis (feedback) are put into practice by decision makers. The most sustainable supply chains are benchmarked by other supply chains. Based on the efficiency scores of Table III, the supply chain No. 5 is ranked 1st, 6th, and 4th in 2012, 2013, and 2014, respectively. Furthermore, the supply chain No. 5 is ranked as the most sustainable supply chain with overall efficiency score of 0.95. Similarly, the supply chains Nos 7 and 17 are ranked as 2nd and 3rd, respectively. The reason why the supply chain No. 5 is superior in ranking is based on the fact that its efficiency score in all years is at a high and acceptable level. Therefore, the overall efficiency of this supply chain is the highest in comparison with the other supply chains. It is noteworthy to state that if we wish to rank the supply chains only based on the efficiency scores in 2014, the supply chain No. 5 would be ranked 4th and in 2013 would be ranked as 6th. The supply chains Nos 15 and 16 are introduced as superior supply chains in 2013, but since this superiority is not sustainable in the years before and after, these supply chains cannot get an overall rank better than 7th and 8th, respectively (Figure 6).

5.2 Managerial implications

Note that the main noticeable outcome of this study is to present a more reliable and realistic model as a novel integrated network dynamic DEA framework for dealing with some shortcomings of the previous models in assessing SSCM. Our proposed method offers a means for managers to monitor and measure efficiency of their production processes.

In recent years, SCM has increasingly become of great importance. Process of evaluation and selection of SCM is one of the most dominant tasks of managers in field of sustainable supply chain. Since decision makers should take into account economic, social, and environmental criteria, these criteria should be identified by decision makers. A variety of mathematical modeling approaches have been utilized in assessing sustainability of supply chains. Mathematical models convert data into information to facilitate strategic and operational decisions. All former approaches, except for DEA, rely on subjective weights of criteria determined by managers. The approach presented in this paper evaluates sustainability of supply chains over multiple periods.

In addition to assessing sustainability of supply chains, in this paper, our model can propose improvement solutions for each inefficient network in any period. Moreover, using the proposed model, weaknesses in each network and in its stages are specified. In Table IV,

Figure 6.
Supply chains'
efficiency score

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2012																	
Farm																	
Inputs																	
Labors' safety cost	−6	−8	−22	−3	–	−4	−8	−5	−6	−7	−3	−10	−22	−20	−11	−12	−11
Environmental costs	−12	−9	−18	−1	–	−9	−11	−22	−11	−18	11	−20	−8	−2	−8	−7	22
Other costs	−17	−16	−23	−14	–	−6	−19	−18	−23	−25	−17	−32	−21	−19	−22	–	−19
Outputs																	
Revenue from tomato sales to factories	170	99	115	109	–	125	226	256	309	66	225	115	289	145	215	55	258
Revenue from tomato sales in markets	18	36	36	41	–	36	34	39	33	18	41	22	36	28	31	35	33
Canning factories																	
Inputs																	
Received tomato from farm	170	99	115	109	–	125	226	256	309	66	225	115	289	145	215	55	258
Environmental costs	−10	−14	−24	−9	–	−9	−17	−9	−9	−−15	−15	−6	−16	−9	−8	−9	9
Labors' safety cost	−5	−11	–	−3	–	−4	−7	−11	−11	−6	−11	−15	−14	−5	−2	−11	−7
Shipping cost	−7	−12	−28	−1	–	−6	12	−4	–	−4	−6	−10	−22	−1	−11	−7	−14
Outputs																	
Tomato pastes ready to use	70,631	46,935	90,638	30,689	–	25,314	21,240	80,005	74,190	55,963	84,600	90,689	84,139	77,258	45,821	36,928	41,852
Chain stores																	
Inputs																	
Tomato pastes ready to use	70,631	46,935	90,638	30,689	–	25,314	21,240	80,005	74,190	55,963	84,600	90,689	84,139	77,258	45,821	36,928	41,852
Shipping cost	−12	19	−28	−12	–	−11	−4	−3	−6	−7	−3	−8	−21	−9	−9	−4	−11
Labor cost	−14	−16	−19	−9	–	−8	34	−8	−18	−18	−18	−32	−21	−20	−17	−10	−14
Outputs																	
Revenue	4,028	3,695	8,159	10,960	–	10,000	6,258	9,550	10,009	9,364	8,512	9,854	7,419	9,520	8,287	6,284	8,271
Degree of customer satisfaction	2	2	3	2	–	2	1	2	–	1	1	1	2	2	2	1	2
Links																	
Unpaid costs																	
Undesirable link	−111	−69	−59	−105	–	−106	−99	−285	−195	−195	−155	−266	−310	225	−208	−55	−64
Not collected revenues																	
Desirable link	231	119	209	266	–	125	206	369	115	309	321	168	298	–	256	215	108
Green R&D																	

(*continued*)

Table IV.
Improvement solutions for inefficient supply chains

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Dual-role link	-15	-45	-96	211	705	88	115	201	-66	-25	-49	-66	83	74	69	-125	66
2013																	
Farm																	
Inputs																	
Labors safety cost	-8	-10	-9	-7	-5	-22	-9	-12	-6	-7	-11	-4	-2	-14	–	–	12
Environmental costs	-14	-4	-5	-6	-3	-15	-8	-7	-3	-9	-5	-6	-10	-8	–	–	–
Other costs	-9	-15	-12	-17	-12	-26	-9	-11	-8	-17	-12	-7	-3	-8	–	–	–
Outputs																	
Revenue of tomato sales to tomato-paste factories	–	25	158	55	87	215	158	147	63	44	87	66	39	154	–	–	–
Revenue of fresh tomato sales to external markets	12	9	15	3	14	22	9	11	8	9	14	4	15	9	–	–	–
Canning factories																	
Inputs																	
Received tomato (purchasing tomato from farm)	–	25	158	55	87	215	158	147	63	44	87	66	39	154	–	–	–
Environmental costs	-7	-11	-14	-3	-9	-22	-14	-16	-21	-8	-14	-8	-11	17	–	–	-2
Employees safety cost	-14	-12	-9	-7	-11	-21	-13	-11	-6	-14	-12	-12	-11	-6	–	–	-5
Shipping cost	-22	-7	-11	-1	-9	-22	-7	-14	-16	-9	-6	-9	-2	-6	–	–	-3
Outputs																	
Tomato pastes ready to use	45,675	32,964	36,852	41,247	39,214	49,301	33,219	29,314	44,200	43,692	42,887	39,625	37,654	33,205	–	–	30,628
Chain stores																	
Inputs																	
Tomato pastes ready to use	45,675	32,964	36,852	41,247	39,214	49,301	33,219	29,314	44,200	43,692	42,887	39,625	37,654	33,205	–	–	30,628
Shipping cost	-12	-9	-18	-3	-11	-33	-15	-23	-14	-11	-9	-10	-8	-15	–	–	-2
Labor force cost	-12	-14	-11	-9	-11	-28	-13	-22	-10	-20	-18	-21	-22	-14	–	–	-5
Outputs																	
Revenue	9,648	8,541	7,418	6,395	7,854	10,852	8,308	9,328	8,317	9,317	8,264	9,656	8,596	10,002	–	–	1,250
Degree of customer satisfaction	2	1	2	–	2	2	2	2	1	2	1	2	1	2	–	–	–

Table IV.

DMUs (supply chains)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Links																	
Unpaid costs																	
Undesirable link																	
Not collected revenues	-189	-205	-226	-174	-218	-269	-163	-254	-147	-226	-234	-198	-244	-264	–	–	-45
Desirable link	158	241	102	105	215	166	213	274	199	265	196	185	144	–	–	–	–
Green R&D																	
Dual-role link	99	-99	63	87	92	-33	66	-30	79	-22	71	63	56	49	–	–	55
2014																	
Farm																	
Inputs																	
Employees safety cost	-8	-9	-18	-14	-12	-15	–	-21	-8	-11	-9	-7	-14	-12	-21	-6	-7
Environmental costs	-9	-10	-9	-18	-16	-16	–	-28	-8	-21	-11	-14	-12	-20	-9	-19	-21
Other costs	-22	-27	-23	-20	-28	-19	–	-34	-16	-15	-17	-21	-19	-24	-22	-23	-18
Outputs																	
Revenue of tomato sales to tomato-paste factories	147	58	21	75	106	85	–	158	95	75	44	21	125	132	136	158	166
Revenue of fresh tomato sales to external markets	9	8	6	4	5	7	–	2	1	3	2	4	–	3	8	6	–
Canning factories																	
Inputs																	
Received tomato (purchasing tomato from farm)	147	58	21	75	106	85	–	158	95	75	44	21	125	132	136	158	166
Environmental costs	-15	-14	-21	-14	-19	-17	–	-22	-10	-14	-16	-22	-12	-3	-21	-13	-12
Employees safety cost	-4	-8	–	–	-7	-5	–	-15	-10	-9	-9	-14	-16	–	-19	–	-5
Shipping cost	-8	-7	-12	-14	–	-9	–	-15	-7	-14	-9	-8	-12	-10	-16	-8	-7
Outputs																	
Tomato pastes ready to use	30,698	26,521	22,964	30,412	28,654	29,301	–	31,964	27,692	26,639	28,963	28,669	19,377	26,394	29,008	25,417	27,608
Chain stores																	
Inputs																	
Tomato pastes ready to use	30,698	26,521	22,964	30,412	28,654	29,301	–	31,964	27,692	26,639	28,963	28,669	19,377	26,394	29,008	25,417	27,608
Shipping cost	-9	-8	-11	-4	-2	-7	–	-24	-11	-11	-6	-10	-12	-1	-19	-10	-4
Labor force cost	-11	-9	-9	-8	–	-11	–	-16	-9	-12	-14	-11	-9	-7	-29	-14	-7
Outputs																	
Revenue	2,015	2,163	2,274	2,361	2,239	2,019	–	2,596	2,165	1,963	2,271	1,939	2,088	1,896	1,936	1,993	2,214
Degree of customer satisfaction	2	2	1	1	–	2	–	2	1	2	1	2	2	–	3	2	1

Table IV.

improvement solutions for inefficient supply chains are provided. As is seen, it is reported that what changes are needed for each DMU in each period to make them efficient. Negative values represent reduction in inputs. Positive values imply an increase in outputs. In addition, the factors that do not need to be changed are indicated by "–."

As is seen in Table IV, for the efficient supply chains no improvement is required. By measuring division efficiency, managers can compare divisions with their competitors. Furthermore, our suggested approach helps managers to determine status of dual-role factors.

5.3 Theoretical contributions and future research directions

NDEA has been developed to model the networks' complexity, whereas traditional DEA models cannot measure supply chains' efficiency with network structures. By estimating the efficiency of the networks, one can get further insights from obtained results and can take proper actions and develop applicable policy to improve sustainability. This paper proposed a network-dynamic DEA model. Using the suggested model, sustainable supply chains were assessed in multiple periods. We determined free links' nature in multiple periods. Moreover, the links' values in multiple periods were used in calculating efficiency of supply chains. One of the main advantages of dynamic DEA is to evaluate DMUs in multiple periods. In this paper, we reached following findings:

- a new additive model of network-dynamic DEA was developed;
- based on series approach, temporal links among network were established;
- nature of free links was determined; and
- the links were outlined in a way that carry-overs of networks are connected in different periods and not in different stages.

Limitations and strengths of this paper can be defined as follows: it is always a big challenge to apprehend complexities of real world in a theoretical model. Accordingly, n real world problems where there are millions of DMUs to be evaluated, we need an approach to deal with big data. In this paper, we did not develop an approach for dealing with big data. The main strengths of this study are two-folds. First, we developed a network and dynamic DEA model for defining free links among periods in terms of desirable and undesirable carry-overs and also connected each network to other networks. Second, we established a novel way for considering multi-stage processes which complements and increases value of two-stage DEA method.

Our approach can be extended for networks with parallel and series-parallel structure. Extending our model using fuzzy data is another research topic. Finally, we recommend prospective researchers to work on DEA models to deal with big data.

References

Ageron, B., Gunasekaran, A. and Spalanzani, A. (2012), "Sustainable supply management: an empirical study", *International Journal of Production Economics*, Vol. 140 No. 1, pp. 168-182.

Azadi, M., Jafarian, M., Farzipoor Saen, R. and Mirhedayatian, S.M. (2015), "A new fuzzy DEA model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context", *Computers & Operations Research*, Vol. 54, pp. 274-285.

Bai, C. and Sarkis, J. (2010), "Integrating sustainability into supplier selection with grey system and rough set methodologies", *International Journal of Production Economics*, Vol. 124 No. 1, pp. 252-264.

Charnes, A., Cooper, W.W. and Rhodes, E. (1978), "Measuring the efficiency of decision making units", *European Journal of Operational Research*, Vol. 2 No. 6, pp. 429-444.

Chen, C. and Yan, H. (2011), "Network DEA model for supply chain performance evaluation", *European Journal of Operational Research*, Vol. 213 No. 1, pp. 147-155.

Chen, Y., Liang, L. and Yang, F. (2006), "A DEA game model approach to supply chain efficiency", *Annals of Operations Research*, Vol. 145 No. 1, pp. 35-49.

Cook, W.D., Zhu, J. and Yang, F. (2010), "Network DEA: additive efficiency decomposition", *European Journal of Operational Research*, Vol. 207 No. 2, pp. 1122-1129.

Dyllick, T. and Hockerts, K. (2002), "Beyond the business case for corporate sustainability", *Business Strategy and the Environment*, Vol. 11 No. 2, pp. 130-141.

Färe, R. and Grosskopf, S. (1996), "Productivity and intermediate products: a frontier approach", *Economics Letters*, Vol. 50 No. 1, pp. 65-70.

Färe, R. and Grosskopf, S. (2000), "Network DEA", *Socio-Economic Planning Sciences*, Vol. 4 No. 1, pp. 35-49.

Färe, R., Grosskopf, S. and Whittaker, G. (2007), "Network DEA", in Zhu, J. and Cook, W.D. (Eds), *Modeling Data Structures Irregularities and Structural Complexities in Data Envelopment Analysis*, Chapter 12, Springer, New York, NY, pp. 209-240.

Govindan, K., Jafarian, A. and Nourbakhsh, V. (2015), "Bi-objective integrating sustainable order allocation and sustainable supply chain network strategic design with stochastic demand using a novel robust hybrid multi-objective metaheuristics", *Computers & Operations Research*, Vol. 62, pp. 112-130.

Govindan, K., Khodaverdi, R. and Jafarian, A. (2013), "A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach", *Journal of Cleaner Production*, Vol. 47, pp. 345-354.

Kao, C. and Hwang, S.N. (2010), "Efficiency measurement for network systems: IT impact on firm performance", *Decision Support Systems*, Vol. 48 No. 3, pp. 437-446.

Khodakarami, M., Shabani, A., Farzipoor Saen, R. and Azadi, M. (2015), "Developing distinctive two stage data envelopment analysis models: an application in evaluating the sustainability of supply chain management", *Measurement*, Vol. 70, pp. 62-74.

Lewis, H.F. and Sexton, T.R. (2004), "Network DEA: efficiency analysis of organizations with complex internal structure", *Computers & Operations Research*, Vol. 31 No. 9, pp. 1365-1410.

Liang, L., Yang, F., Cook, W.D. and Zhu, J. (2006), "DEA models for supply chain efficiency evaluation", *Annals of Operations Research*, Vol. 145 No. 1, pp. 35-49.

Likert, R. (1932), "A technique for the measurement of attitudes", *Archives of Psychology*, Vol. 22 No. 140, pp. 1-55.

Noorizadeh, A., Mahdiloo, M. and Farzipoor Saen, R. (2011), "Supplier selection in the presence of dual-role factors, non-discretionary inputs and weight restrictions", *International Journal of Productivity and Quality Management*, Vol. 8 No. 2, pp. 134-152.

Rashidi, K., Shabani, A. and Farzipoor Saen, R. (2015), "Using data envelopment analysis for estimating energy saving and undesirable output abatement: a case study in the organization for economic co-operation and development (OECD) countries", *Journal of Cleaner Production*, Vol. 105, pp. 241-252.

Sengupta, J.K. (1995), *Dynamics of Data Envelopment Analysis*, Kluwer Academic Publishers, Dordrecht.

Seuring, S. and Müller, M. (2008), "From a literature review to a conceptual framework for sustainable supply chain management", *Journal of Cleaner Production*, Vol. 16 No. 15, pp. 1699-1710.

Sueyoshi, T. and Goto, M. (2010), "Should the US clean air act include CO2 emission control? Examination by data envelopment analysis", *Energy Policy*, Vol. 38 No. 10, pp. 5902-5911.

Tavassoli, M., Faramarzi, G.R. and Farzipoor Saen, R. (2014), "Efficiency and effectiveness in airline performance using a SBM-NDEA model in the presence of shared input", *Journal of Air Transport Management*, Vol. 34, pp. 146-153.

Tone, K. and Tsutsui, M. (2010), "Dynamic DEA: a slacks-based measure approach", *Omega*, Vol. 38 Nos 3-4, pp. 145-156.

Tone, K. and Tsutsui, M. (2014), "Dynamic DEA with network structure: a slacks-based measure approach", *Omega*, Vol. 42 No. 1, pp. 124-131.

Tseng, M.L., Lim, M. and Wong, W.P. (2015), "Sustainable supply chain management: a closed-loop network hierarchical approach", *Industrial Management & Data Systems*, Vol. 115 No. 3, pp. 436-461.

Wong, W.P., Jaruphongsa, W. and Lee, L.H. (2008), "Supply chain performance measurement system: a Monte Carlo DEA-based approach", *International Journal of Industrial and Systems Engineering*, Vol. 3 No. 2, pp. 162-188.

Wong, W.P. and Wong, K.Y. (2007), "Supply chain performance measurement system using DEA modeling", *Industrial Management & Data Systems*, Vol. 107 No. 3, pp. 361-381.

Wu, K.J., Liao, C.J., Tseng, M.L. and Chiu, K.K.S. (2016), "Multi-attribute approach to sustainable supply chain management under uncertainty", *Industrial Management & Data Systems*, Vol. 116 No. 4, pp. 777-800.

Yousefi, S., Shabanpour, H. and Farzipoor Saen, R. (2015), "Selecting the best supply chain by goal programming and network data envelopment analysis", *RAIRO-Operations Research*, Vol. 49 No. 3, pp. 601-617.

Yousefi, S., Shabanpour, H., Fisher, R. and Farzipoor Saen, R. (2016), "Evaluating and ranking sustainable suppliers by robust dynamic data envelopment analysis", *Measurement*, Vol. 83, pp. 72-85.

Yu, M.M. and Lin, E.T.J. (2008), "Efficiency and effectiveness in railway performance using a multi-activity network DEA model", *Omega*, Vol. 36 No. 6, pp. 1005-1017.

Yu, M.M., Ting, S.C. and Chen, M.C. (2010), "Evaluating the cross-efficiency of information sharing in supply chains", *Expert Systems with Applications*, Vol. 37 No. 4, pp. 2891-2897.

Zhu, Q., Sarkis, J. and Geng, Y. (2005), "Green supply chain management in China: pressures, practices and performance", *International Journal of Operations & Production Management*, Vol. 25 No. 5, pp. 449-468.

Corresponding author
Reza Farzipoor Saen can be contacted at: farzipour@yahoo.com