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The origins, development and future directions of Data Envelopment Analysis approach in transportation systems

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Abstract

Over the last two decades, application of Data envelopment analysis (DEA) in transportation problems have gained considerable research attention. This paper presents a literature review and classification of the applications of DEA in transportation systems (TSs). First by classifying 40 papers from 2007 to 2018, the origins of DEA in transportation problems have been reviewed. Then the development and an overall view of DEA applications in TSs have been presented. We have classified the applications of DEA into six different contexts. In each context, published papers have deeply been analyzed. Content of analysis includes “Number of published papers during the time”, “target journals”, “countries”, “keyword frequency”, “most cited papers”, “map of most co-cited publications”. More important, we reported the “inputs and outputs variables” used in each paper. Further “a review of the selected papers” and “gaps / future research directions” have been given within each cluster. The results show that DEA is one of the most useful approach in evaluating TSs for policy makers. On the other hand, DEA can help the decision makers in transportation especially regarding environmental factors, sustainable development and eco-design. Finally, we proposed subjects for future researches including guidance for new studies in the field of DEA applications in TSs.

Keywords: Data Envelopment Analysis; Transportation Systems; Highway/ Railway/ Air/ Maritime Transportation; Public Sector Evaluation.

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1. Introduction

Formation and development of civilizations have been affected by the transportation throughout history. Nowadays one important characteristic of developed countries is having an efficient, safe and advanced transportation system (TS). Increasing rate of the world population results lead to the need for different TSs. The transportation systems are expanding very rapidly, and so it is important to make sure the systems are efficient in order to save time and costs as well as safety.

Development of TSs have resulted in increasing energy consumption, traffic, transportation accident leading to loss of life and property and greenhouse gas emission, also change in land use because of transportation infrastructures. Transportation sector is one of the major energy consumer which produce a lot of pollutions in the world (Fuglestvedt et al., 2008). For example, in USA in 2014, transportation ranked second after the electricity power plants, among the most polluting sectors (SEPA, 2017). According to intergovernmental panel on climate change report in 2014, by producing 14% of the total pollution around the world, transportation’s ranking is 4 (see Figure 1) (IPCC, 2017). Therefore, by reducing greenhouse gas emissions produced by the transport sector, it is expected to see a significant reduction in air pollution, acid rain, climate change and etc. (ECT, 2007). The statistics also show that about 1.25 million people die as a result of road accidents in each year. It is expected that the road traffic accident will be the seventh leading cause of death in 2030 (WHO, 2016). In term of supply chain management, by improving transportation methods, costs can be reduced by 15-20% (4flow, 2017). Therefore, it is important to survey the existing publication on the performance of TSs.

Four decades after the introduction of Data Envelopment Analysis (DEA) by Charnes et al. (1978), this method has been applied in various subjects, including evaluating of TSs. According to Emrouznejad and Yang (2017), in the last three years transportation is ranked 4th most common application using DEA.

This paper presents a literature review and classification on the applications of DEA in TSs. More than 600 articles from 1989 to 2018 in Google scholar, Web of knowledge and Scopus have been surveyed. Only journal papers which have been published in English language are considered. Conference papers, books and non-English papers have
not been included. First by classifying 40 most cited papers from 2007 to 2018, DEA models which have widely been used in evaluating the performance of TSs, are explained. Then an overall view of DEA applications in TSs has been presented. We classified transportation applications in six different categories including: (1) DEA and highway transportation (2) DEA and air transportation (3) DEA, ports and maritime transportation (4) DEA and railway transportation (5) DEA, Eco-design, sustainable development and green issues in transportation (6) DEA and other transportation research. A review of the selected papers, gaps and future directions for research have been presented for each category. Further, we have identified trend of researches’ subjects. While past papers only provide overall statistical information about research in transportation and DEA field, this article presents a comprehensive analyzes of the most common used models, keywords, target journals, map of co-cited papers/authors and etc, in different TSs, separately. To the best of our knowledge, this article is the most comprehensive and the first study that has analyzed, classified and reviewed DEA applications in all major transportation fields. Further to this and for the first time a Critical Path Method (CPM) of DEA applications in TSs is also presented.

The rest of this paper is organized as follows: Method and search algorithm is presented in section 2. Section 3 presents a brief introduction of most DEA models used in transportation problems. An overall view and some important analysis for DEA applications in TSs have been presented in section 4. In section 5, compressive reviews of DEA applications in all considered categories are presented, separately. Finally, concluding remarks and directions for future research are provided in Section 6.

2. Method and search algorithm

Google scholar, Web of knowledge and Scopus have been considered as databases for articles search. First, using proposed algorithm in Table 1 list of primary articles has been prepared. Then with a closer look, related articles were identified and filtered. Only published papers in journal and English language have been considered. PRISMA (Moher et al., 2009) statement has been used in systematic search, reviews and meta-analyses (See Figure 2).
3. Most common DEA models applied in transportation systems

In this section first by classifying 40 most cited papers from 2007 to 2018, DEA models that have been widely used in evaluating the performance of transport systems, are identified. Then 3 selected models have introduced briefly. According to Table 3, CCR (Charles, Cooper & Rhodes), BCC (Banker, Charles & Cooper) and SBM (Slacks-Based Measure) are the most popular models used in the literature. (see also Figure 3):

---------------- [Table 2 about here] ----------------
---------------- [Figure 3 about here] ----------------

3.1. The CCR model

The main idea of DEA is measuring relative efficiency of homogeneous set of decision making units (DMUs). Indeed, DEA believes that performance of a DMU should be evaluated in the presence of competitors (other DMUs). The first DEA model has proposed by Charnes et al. (1978). Suppose there are \( n \) DMUs, where each \( DMU_j \) \((j = 1,\ldots,n)\) consumes \( m \) inputs, \( x_{ij} \) \((i = 1,\ldots,m)\), to produce \( s \) outputs, \( y_{rj} \) \((r = 1,\ldots,s)\). Assume \( u_r \) \((r = 1,\ldots,s)\) and \( v_i \) \((i = 1,\ldots,m)\) are the relative importance of each output, and input, respectively. The input-oriented CCR DEA model to evaluate the performance of \( DMU_O \) is presented as follows:

Max \( \sum_{r=1}^{s} u_r y_{ro} \)

\[ s.t. \]
\[ \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \quad j = 1,\ldots,n \]
\[ \sum_{i=1}^{m} v_i x_{io} = 1, \]
\[ u_r > 0, \quad r = 1,\ldots,s, \]
\[ v_i > 0, \quad i = 1,\ldots,m \]

This model is based on the assumption of constant returns to scale (CRS) and the dual form of model (1) is as follow:
Min $\theta$

s.t.

\begin{align*}
\sum_{j=1}^{n} \lambda_{j} x_{ij} & \leq \theta x_{io}, \quad i = 1, \ldots, m \\
\sum_{j=1}^{n} \lambda_{j} y_{rj} & \geq y_{ro}, \quad r = 1, \ldots, s \\
\lambda_{j} & \geq 0, \quad j = 1, \ldots, n.
\end{align*}

**3.2. The BCC Model**

Under variable returns to scale (VRS) assumption the convexity constraint should be added to the model, hence models (1) and (2) can be formulated as follows. In the literature these models are referred as BCC (Banker et al., 1984):

Max $\sum_{r=1}^{s} u_{r} y_{ro} - u_{0}$

s.t.

\begin{align*}
\sum_{r=1}^{s} u_{r} y_{rj} - u_{0} - \sum_{i=1}^{m} v_{i} x_{ij} & \leq 0, \quad j = 1, \ldots, n \\
\sum_{i=1}^{m} v_{i} x_{io} & = 1, \\
u_{0} & \text{ is free in sign} \\
u_{r} & > 0, \quad r = 1, \ldots, s, \\
v_{i} & > 0, \quad i = 1, \ldots, m
\end{align*}

The dual form of Model (3) is as follows (Banker et al., 1984):

Min $\theta$

s.t.

\begin{align*}
\sum_{j=1}^{n} \lambda_{j} x_{ij} & \leq \theta x_{io}, \quad i = 1, \ldots, m \\
\sum_{j=1}^{n} \lambda_{j} y_{rj} & \geq y_{ro}, \quad r = 1, \ldots, s \\
\sum_{j=1}^{n} \lambda_{j} & = 1 \\
\lambda_{j} & \geq 0, \quad j = 1, \ldots, n.
\end{align*}
The above models are presented as input-oriented form to consider reduction in input values. Similar models can be formulated in the output-orientation to consider increase in output values.

3.3. The SBM model

The slacks-based Model (SBM) is the third most popular model used for evaluating TSs. Most researchers who study existing TSs have used SBM model in order to determine surplus in inputs/undesirable outputs and slacks of desirable outputs to improve the system by controlling surplus/slack values. SBM model under CRS assumption is as follows (Tone, 2001):

\[
\begin{align*}
\min \theta &= \frac{1 - (1 / m) \sum_{i=1}^{m} s_i^- / x_{i0}}{1 + (1 / s) \sum_{r=1}^{s} s_r^+ / y_{ro}} \\
\text{s.t.} \quad &\sum_{j=1}^{n} \lambda_j x_{ij} = x_{i0} - s_i^- , \quad i = 1, \ldots, m \\
&\sum_{j=1}^{n} \lambda_j y_{rj} = y_{ro} + s_r^+ , \quad r = 1, \ldots, s \\
&\lambda_j \geq 0 , \quad j = 1, \ldots, n \\
&s_i^-, s_r^+ \geq 0 , \quad \forall i, r
\end{align*}
\]

(5)

where \(s_i^-\) and \(s_r^+\) are surplus and slack values, respectively. A DMU is efficient if and only if \(\theta^* = 1, s_i^-, s_r^+ = 0 \\forall i, r\).

SBM considers all inefficiencies where CCR considers technical inefficiencies. For considering VRS assumption, \(\sum_{j=1}^{n} \lambda_j = 1\) must be added to model (5).

4. DEA applications in transportations: an overall view

In this study, the published papers have been classified and reviewed in six different sections including DEA applications in highway transportation, air transportation, maritime transportation, railway transportation, sustainability and environmental issues in transportation and other transportation issues. We first, in this section, give an overall view of published papers using DEA in any type of transportation issues.

Figure 4 shows the topic of a third of related papers are in air transportation system, and as seen in Figure 5, more than 80% of papers have been published in last 10 years are related to use of DEA in air transportation systems, and so this became a very interesting
topic for researchers in recent years. As it is clear from Figure 6, number of papers that have focused on the DEA applications in all considered sections, is rapidly increasing over recent years. In all sections, more than 75% of identified papers, are in the last 10 years, that shows increasing importance of these subjects. Figure 7 shows the subject area of the identified papers in this section.

Table 3 and

Table 4 present the most cited papers and most active authors, respectively. By 312 citations, Tongzon (2001) is most cited papers, which is related to ports and maritime TSs. Also Yu and Barros are two most active authors. Yu focused on air, highway and railway TSs and Barros mainly focused on air and maritime TSs. Most active journals in each section and in all area of type of transportation issues are listed in Table 5. “Journal Of Air Transport Management” and “Transportation Research Part A Policy And Practice” are two journals with most published papers. Top 10 countries which have published most papers related to DEA applications in TSs are presented in Table 6. Researchers of United states and China are two active countries, with 109 published articles. Also Table 7 shows the keywords that have most frequency across the DEA and TSs literature in each section and in overall.

Recently, using social network analysis (SNA) have become very popular for studying papers citation. This method leads to understand different aspects of under study fields such as co-citation, collaboration among researchers, knowledge patterns, gaps and emerging knowledge trends within disciplines (Emrouznejad and Marra, 2014, 2017). In this study, by using mapping technique and SNA, we will try to achieve these targets (for more information about mapping and SNA technics and their advantages please see Emrouznejad and Marra (2014)). In each section, using VOSviewer and Pajek softwares, maps of most co-occurrence keywords and co-authorship network related to DEA applications in TSs have been provided. Maps of most co-occurrence keywords, co-authorship network and most co-cited papers are presented in Figure 8, Figure 9 and Figure 10, respectively. Large shapes dimension related to keyword/author which means it has more frequent between others. Also the links with more width represents a strong
relation between two individuals. The most co-cited papers are listed in Table 8. Charnes et al. (1978), which introduced DEA for the first time, is the most co-cited paper. The rest of the paper will focus on each subject area in details.

5. DEA and its applications in transportation systems

5.1. DEA and highway transportation systems

In this section details of studies which have focused on DEA applications in highway TSs have been investigated.

Based on surveying all 63 identified papers, considered inputs and outputs for evaluating the highway TSs by DEA, have presented in Table 5.1.1. Table 5.1.2 presented highly cited papers in DEA applications in highway TSs. Also, the maps of most co-occurrence keywords and co-authorship network have been shown in Figure 5.1.1 and Figure 5.1.2, respectively. By using Critical Path Method (CPM), abstract, keywords, references and citations have been surveyed and the evolution and direction of knowledge accumulation in DEA applications in highway TSs have been shown in Figure 5.5.3. Finally, a review of selected papers has presented in Table 5.1.3.

Based on Figure 5.1.1, the most co-occurrence keywords in the published papers are DEA (data envelopment analysis), environmental efficiency, sustainability, highway maintenance and traffic safety. Data envelopment analysis and highway maintenance are two most co-occurrence keywords. By analyzing this figure, the main and hot research directions in DEA applications in highway TSs and research gaps can be identified. Co-authorship network presented in Figure 5.1.2 shows a strong relationship between Cook, Kazakov and Roll, who have focused on DEA applications in highway maintenance problems. Wade Cook has the most co-authorship with other researchers. Based on Figure 5.1.2, authors who are more eager to cooperate with other researchers can be identified and researchers can try to cooperate with them in this field. Figure 5.5.3 represents evolution and direction of knowledge accumulation and Table 5.1.3 shows the literature of DEA applications in highway TSs. Analyzing Figure 5.5.3 and Table 5.1.3 shows that most of the published papers have focused on three main topics: (a) repair and maintenance
problems of highways (b) road traffic accidents management (c) the problem of environmental and energy consumption in highway transportation. The first paper has been published by Cook et al. (1990). They studied the maintenance problem in highway TS. This study was developed by Kazakov et al. (1989), Cook et al. (1991) and Roll et al. (1991). Until 2009 the main subject of the researches was repair and maintenance problem, where from 2010 the environmental and safety issues have become more interesting subjects for authors. Rogers and Weber (2011) evaluated the CO2 emissions and fatalities tradeoffs in highway transportation systems. After that Leal et al. (2012) developed their work by considering different environmental factors as inputs and outputs for prioritizing different bioethanol highway transportation modes. The environmental issues in highway TSs still is an interesting topic. Many papers related to this subject have tried to evaluate the existing systems and proposed scenarios/policies by considering CO2 emission and other sustainability factors. Recently do Castelo Gouveia and Clímaco (2018) applied DEA to evaluate fuel tax policies to overcome emission problems in highway TSs. Safety in highway TSs is another topic that recently have attracted many researches attention. The research of Vaziri (2010) was one of the first papers in this area. Their paper studied roadway accidents. This work developed by Egilmez and McAvoy (2013) and Alper et al. (2015) and also is a hot topic.

For future research, studying existing highway transportation systems in specific region, from various perspectives like environmental, economic and social sustainability or user/manager perspectives is an interesting subject and the purpose of the study can be identifying surplus and slacks values, providing solutions to improve the performance and identifying alternative systems.

A lot of papers have used a single-period data set for local TSs, while it seems using secondary datasets such as detailed socioeconomic factors, more accurate and multi-period data set of local, regional and national TSs can lead to better results and more effective policies. Highway/road TSs are the most polluted and energy consumer transportation system, therefore reducing energy consumption and improving environmental performance of these systems, can be the subject of future researches.

Based on road traffic in a lot of cities, issues like traffic enforcement camera locating, traffic light locating, traffic police management and etc. would be new challenging problems which can be surveyed by DEA.
Evaluating newly emerged traffic modes and management strategies/policies such as car sharing for low-income peoples specially in peak times, is an important issue that can be surveyed using DEA. Presentation customized DEA models to evaluate highway TSs and different investment highway transportation projects is another interesting research direction. Also, DEA can be applied to evaluate the effects of economic changes on the performance of highway TSs and other TSs in developing countries.

Many governmental interventions such as fuel tax, fuel price, subsidies and public transportation tickets prices can affect the performance of highway TSs significantly. Based on the interventions, number of accidents, traffic volume, emissions and etc., can be reduced or increased. DEA is useful to evaluate these interventions.

Most transportation accidents occur on Highways/roads. How can we reduce the accidents? It can be interesting to answer this question by using DEA. Also highway management and its impacts on systems’ performance, is a challenging subject to study. The issue of combined transportation and mode choice in highway transportation are other interested problems to study.

5.2. DEA and air transportation systems

Among the all considered subjects, the highest number of published papers in DEA and transportation field is related to air transportation.

221 published papers have identified and 57 papers were selected for review. The number of papers that have focused on the DEA application in air TSs, is rapidly increasing over the recent years. 97 papers of 221 papers have published in last 5 years. By surveying all identified papers, considered inputs and outputs for evaluating the air TSs by DEA, have presented in Table 5.2.1. Table 5.2.2 presented most cited papers related to DEA applications in air TSs. Also, the maps of most co-occurrence keywords and co-authorship network have been shown in Figure 5.2.1 and Figure 5.2.2, respectively. After surveying title, abstract, keywords, references and citations by using CPM, evolution and direction of knowledge accumulation in DEA applications in air TSs have been shown in Figure 5.2.3. Finally, a review of selected papers has presented in Table 5.2.3.

Based on Figure 5.2.1, the most co-occurrence keywords in the published papers are DEA (data envelopment analysis), technical/operational efficiency, benchmarking, airport and airlines. Data envelopment analysis and airport(s) are two most co-occurrence
keywords. By analyzing this figure, the main and hot research directions in DEA applications in air TSs and research gaps can be identified. Investigating the co-authorship network presented in Figure 5.2.2 shows a strong relationship between (Pels, Nijkamp and Rietveld) and (Gitto and Mancuso). Pels, Nijkamp and Rietveld have focused on DEA applications in performance assessing of European airports. Gitto and Mancuso mainly have used MI and bootstrapped DEA to performance evaluation of airports. Adler, Pels, Gitto and Mancuso have more co-authorship with other researchers. Based on Figure 5.2.2, the authors who are more eager to cooperate with other researchers can be identified and authors can try to cooperate with them in this field. Analyzing the evolution and direction of knowledge accumulation presented in Figure 5.2.3 and reviewing the literature of DEA applications in air TSs (Table 5.2.3) show that most of the published papers in this field have focused on five main issues: (a) analyzing the performance of airlines (b) performance assessment of airports (c) the efficiency of air roads (d) cost efficiency and service efficiency of provided services to passengers and cargo transportation (e) analyzing performance of airports and airlines during the time. The first paper has been published by Chan and Sueyoshi (1991), who analyzed the performance of airline industries based on competition and different strategies. Evaluating the performance of airlines still is a hot topic and researchers have considered various modern issues in their analysis such as alliance, technologies and etc. (Kottas and Madas, 2018). First paper about the airport was published by Parker (1999) and still it is an interesting challenge for researchers. Until 2004 the main subjects of the studies were performance analyzing of airline industries/companies and airports. Since 2005 new subjects have been added in the literature. Investigating performance of air routes started by Chiou and Chen (2006) and continued by Lin (2008). In addition to operational efficiency, researchers tried to evaluate technical and economic performance of airlines and airports, too. Barros and Dieke (2008), Barros (2008), Barros and Dieke (2008) and Lam et al. (2009). Recently researchers used multi-period data and combined statistical models and DEA models in their analysis and tried to find a rational relation between effective factors and different efficiency scores of airlines and airports(Liu, 2017; Omrani and Soltanzadeh, 2016; Örkcü et al., 2016).

Large number of papers have studied efficiency changes of airports and airlines during a special time period or before/after a crisis or policy. To analyze the performance of air TSs, MI has been used more than any other models.
For future research, studying existing systems from various perspectives like environmental, economic and social sustainability, and users/managers perspectives is an interesting subject and the purpose of the study can be identifying surplus and slacks values, providing solutions to improve the performance and identifying alternative systems.

Other research directions can be assessing the efficiency of airports in a special region such as a country, continent, union or a company before/after a special event such as a sanctions, revolution, new rules, new aircraft. Also, adding new companies to a set of existing companies during a period can be considered for future research. Customizing DEA models for performance evaluation in air TSs is a challenging but an interesting issue. Also, negative and undesirable inputs/outputs (such as noise, pollution and etc.), have not considered by most of the researches. While undesirable inputs/outputs strongly affect efficiency score and ranks.

Surveying root risks of airports is a new and interesting issue which can be analyzed by DEA. Combining learning algorithms, system dynamic models and DEA for designing an intelligent system would be useful for such studies.

Data in air TSs is not always deterministic; therefore, developing new DEA models or customizing old DEA models for performance evaluation of air TSs in presence of non-deterministic data such as fuzzy numbers, random numbers, or even missing data is another research direction.

Identifying different effective factors on airlines performance, investment and depreciation variables using DEA is a good idea for future researches. Analyzing the effects of different price levels on inputs, outputs and efficiency is a challenge for future studies. Routing for airlines is a crucial issue, therefore optimal routing is an interesting future research for DEA applications in air TSs.

DEA can be applied to explore the effect of alliance membership on the comparative efficiency measure of national or international airlines. Operational, technical and service efficiency of air TSs can be evaluated by DEA. The authors should use DEA models to survey the role of market mechanisms in achieving sustainable targets in air TSs.
Recently, fuel consumption efficiency in air transportation has converted to a critical issue, which can be the subject of various future studies in this field. MI and panel data based DEA models are the most suitable DEA models for these studies.

5.3. DEA, ports and maritime transportation

Ports are one of the most important sectors of commerce and transportation in a country. Productivity of ports and maritime transportation are among the important and complex issues in the contemporary world economy. If international and domestic ports want to identify their advantages/disadvantages and potential opportunities for success and growth in the global competitive environment, it is necessary for them to evaluate their performance in all aspects. Hence efficiency and performance assessment of maritime TSs, especially in the ports, has attracted enormous interest.

157 published papers in DEA applications in evaluation of ports and maritime TSs have identified, then 35 papers were selected for review. As other sections, number of published papers in this section, is rapidly increasing over the recent years. 67 papers of 150 papers have published in last 5 years that shows increasing importance of this subject. Used inputs and outputs for evaluating ports and maritime TSs by DEA, have presented in Table 5.3.1.

Table 5.3.2 presented most cited papers related to DEA applications in ports and maritime TSs. Also, the maps of most co-occurrence keywords and co-authorship network have shown in Figure 5.3.1 and Figure 5.3.2, respectively. After surveying title, abstract, keywords, references and citations by using CPM, evolution and direction of knowledge accumulation in DEA applications in maritime TSs have been shown in Figure 5.3.3. Finally, a review of selected papers has presented in Table 5.3.3.

Based on Figure 5.3.1, the most co-occurrence keywords in the published papers are DEA (data envelopment analysis), container terminals, ports, sea ports, logistic and bootstrap. By analyzing this figure, the main and hot research directions in DEA applications in maritime TSs and research gaps can be identified. Investigating the co-authorship network presented in Figure 5.3.2 shows a strong relationship between Barros and Wanke, which have focused on performance assessing of Brazilian sea ports. Also Barros and Wanke have more co-authorship with other researchers. Based on Figure 5.3.2, authors who are more eager to cooperate with other researchers can be identified and the
authors can try to cooperate with them in this field. The results of searches show that more than 70% papers in DEA applications in ports and maritime transportation have published in last 8 years, which introduces this field as one of the hot issues for research. Analyzing the evolution and direction of knowledge accumulation is presented in Figure 5.3.3. Reviewing the literature of DEA applications in ports and maritime TSs (Table 5.3.3) shows that most of the published papers in this field have focused on four main issues: (a) analyzing the performance of international sea ports (b) performance assessment of container terminal ports (c) cost, operational and technical efficiency of ports (d) surveying the effect of private sector participation, governance structure, new investments and infrastructure of ports on performance and efficiency. The first paper has been published by Roll and Hayuth (1993), which was the first paper that had analyzed performance of sea ports. This study developed by Martinez-Budria et al. (1999). Instead of single period data, Martinez-Budria et al. (1999) considered panel data in evaluating Spanish ports performance. Analyzing the performance of seaports from different perspectives is one of the earlier application of DEA and maritime transportation studies, and still is it is one of the hot topic for researchers. From 2002, new problems in maritime TSs considered by some articles such as Itoh (2002). These studies were related to evaluating the performance of container ports. Until 2010 the main subjects of published researches were technical and operational performance analyzing of sea ports and container ports. From 2011 new subjects have been added to the literature including environmental analysis of maritime TSs Bergantino and Musso (2011). Future research could focus on analyzing these three major and perhaps the most important is environmental and international subjects.

For future researches, studying existing systems from various perspectives like environmental, economic and social sustainability is an interesting subject and the purpose of the study can be identifying surplus and slacks values, providing solutions to improve the performance and identifying alternative systems.

In many countries, especially in developing countries, ports and maritime TSs have governmental structure. Therefore, partnership, investment and management of private sector in these countries could be the context of future studies. A large number of papers has studied efficiency changes of ports during a special time period. MI, panel data based DEA models, SFA, regression analysis and bootstrapped DEA model have been used more
than any other models. For future researches, efficiency of ports in a special region such as a country, continent, union or a company before/after a special event such as a sanctions, revolution and new rules can be analyzed. Also, adding new companies to a set of existing companies during a period can be considered for future research.

According to the sustainability targets, it must be analyzed how ports can operate efficiently while pursuing diverse sustainable development objectives. Different environmental regulations must be evaluated, and the best policies should be identified. Studying, analyzing and designing combined transportation modes such as rail-maritime transportation is interesting and challenging.

Considering more factors affecting efficiency of maritime TSs as inputs and outputs, will lead to more precise analysis. Identifying more criteria and efficiency measures can be other research direction.

Recently studying the issues related to sustainability, sustainable development and emission reduction in maritime TSs have attracted many researchers. Future direction can focus on these subjects. Analyzing the effects of different management models on the efficiency of maritime TSs using DEA is another suggestion.

In real-world studies, there are a great number of uncertainties. Developing a DEA model for evaluating ports and maritime TSs using uncertain data like as fuzzy DEA model, can be an interesting research direction. Also missing data is an important issue in DEA. Developing a framework to study the performance of maritime TSs in the presence of missing data will be very useful. MI and panel data based DEA models are the most suitable DEA models for these studies.

5.4. DEA and railway transportation

According to Kyoto Protocol, all countries around the world must take actions to reduce their greenhouse gas emissions. Selecting more efficient and eco-friendly TSs is an important action. The rail transportation as one of the greenest and safest TSs has attracted the most countries attention. Due to advantages of railway transportation, studying and improving the efficiency of existing systems, increasing level of service, safety and overall productivity of the system, are the subject of a lot of researches.

74 published papers have identified and 29 papers were selected for review. Such as the previous sections, number of published papers in this section, is rapidly increasing. 34
papers of 74 papers (more than %45) have published in last 5 years that shows the increasing importance of this subject. By surveying the identified papers, used inputs and outputs for evaluating railway TSs by DEA, have presented in Table 5.4.1. Table 5.4.2 presented most cited papers related to DEA applications in railway TSs. Also, maps of most co-occurrence keywords and co-authorship network have shown in Figure 5.4.1 and Figure 5.4.2, respectively. By using CPM, title, abstract, keywords, references and citations have been surveyed and the evolution and direction of knowledge accumulation in DEA applications in railway TSs have been shown in Figure 5.4.3. Finally, a review of selected papers has presented in Table 5.4.3.

Based on Figure 5.4.1, the most co-occurrence keywords in the published papers are DEA (data envelopment analysis), railway(s), freight, passengers and technical efficiency. By analyzing this figure, the main and hot research directions in DEA applications in railway TSs and research gaps can be identified. Investigating the co-authorship network presented in Figure 5.4.2 shows a strong relationship between Yu and Lin, who have focused on environmental and technical efficiency of railways. Also Yu has the most co-authorship with other researchers. Based on Figure 5.4.2, the authors who are more eager to cooperate with other researchers can be identified and the authors can try to cooperate with them in this field. The searches show that more than %60 of papers in DEA applications in railway transportation have published in last 8 years that introduces this field as one of the hot topics for research. Analyzing the evolution and direction of knowledge accumulation presented in Figure 5.4.3 and reviewing the literature of DEA applications in railway TSs (Table 5.4.3) show that most of the published papers in this field have focused on five main issues: (a) analyzing the performance of railway transportation companies in passengers and cargo transporting (b) performance assessment of railway TSs by considering environmental factors (c) Locating of urban railway stations (d) surveying the effect of private sector participation, governance structure, new investments and infrastructure on performance and efficiency (e) studying the trend of efficiency changes during the time using panel data based DEA models and MI. Moesen (1994) published the first paper in this category, then Cowie and Riddington (1996) and Chapin and Schmidt (1999) developed Moesen (1994)’s study. The article of Cowie and Riddington (1996) was a start for evaluating railways performance, while Chapin and Schmidt (1999) encouraged other researches to study railway fright transportation. Until
2003 the main subjects of the researches were fright and railway performance analysis, while from 2004 new subjects have been added in the literature, including environmental analysis (started by Lan and Lin (2005)), safety (started by Noroozzadeh and Sadjadi (2013)), passenger transportation (started by Hilmola (2010)) and site selection (started by Mohajeri and Amin (2010)).

Private sector participation, sustainable development, energy consumption, environmental issues, identifying the surplus and slacks values, providing solutions to improve the performance in railway TSs are interesting subjects which could be some of the research directions.

In many countries, especially in developing countries, railway TSs have governmental structure. SO partnership, investment and management of private sector in these countries could be a context of future studies. Specially analyzing the effects of privatization on performance and efficiency assessment before/after privatization is a challenging research subject.

MI and panel data based DEA models have used more than any other models for studying changes of efficiency during the time. As other future researches directions, assessing the efficiency of railway TSs in a special region such as a country, continent, union or a company before/after of a special event such as sanctions, revolution and new rules in during a period, could be interesting subjects.

Surveying the railway transportation sustainability is an interesting subject. Monitoring and evaluating safety in the railway TSs is an important problem which can be analyzed by DEA. A lot of supply chains use railway TSs to distribute their products. Studying, evaluating and designing efficient railway TSs for better integration of railway TSs and supply chain management are other research directions.

To identify direct causes which leads to inefficiency/efficiency of railway TSs, maybe it will be useful to combine DEA methods with other statistical and non-statistical methods. Considering resilience engineering factors in performance analyzing has attracted attentions. Combing resilience engineering and DEA in transportation will lead to interesting results.
Investigating factors affecting the performance of different parts of railway TSs, can be one of the most important applications of DEA. Also, DEA can be applied to analyze different managerial and operational strategies and their effects on railway TS.

Customizing a DEA model for performance evaluation of railway TSs is another research direction. MI and panel data based DEA models are the most suitable DEA models for these studies. Also, an international evaluation for identifying weaknesses and deficiencies of assessment systems could be helpful.

5.5. DEA, Eco-design, sustainable development and green issues in transportation

Emissions, energy and fuel consumption of TSs are among the most challenging concerns of many countries in the world. Due to increasing population growth and demand for transportation, it seems that environmental issues in transportation will be a research priority. DEA can be used as one of the best tools for identifying weaknesses and potential solutions to improve existing systems.

90 published papers in this section have been identified and 18 papers have been selected for review. 57 papers of 90 identified papers (more than 60%) have been published in the last 5 years that shows papers have focused on the DEA applications in environmental issues of TSs, are rapidly increasing. Considered inputs and outputs for evaluating environmental perspectives of TSs by DEA have been presented in Table 5.5.1. Table 5.5.2 presented most cited papers related to DEA applications in environmental issues of TSs. Also, the maps of most co-occurrence keywords and co-authorship network have been shown in Figure 5.5.1 and Figure 5.5.2, respectively. By using CPM, title, abstract, keywords, references and citations have been surveyed and the evolution and direction of knowledge accumulation in DEA applications in environmental issues of TSs have been shown in Figure 5.5.3. Finally, a review of selected papers has been presented in Table 5.5.3.

Based on Figure 5.5.1, the most co-occurrence keywords in the published papers are DEA (data envelopment analysis), transportation, environmental efficiency, lifecycle assessment, sustainable and undesirable outputs. By analyzing this figure, the main and hot research directions in DEA applications in environmental issues of TSs and research gaps can be identified. Investigating the co-authorship network presented in Figure 5.5.2 shows a strong relationship between (Wu, Zhu and Chu) and (Wu and Liang) who have focused on environmental efficiency of Chinese TSs. Also, Wu has more co-authorship with other
researchers. Based on Figure 5.5.2, authors who are more eager to cooperate with other researchers can be identified and the authors can try to cooperate with them in this field. Publishing more than %85 of papers in DEA applications for evaluating environmental perspectives of TSs in last 8 years, introduces this field as a hot issue for research. Analyzing the evolution and direction of knowledge accumulation presented in Figure 5.5.3 and reviewing the literature (Table 5.5.3) show that most of the published papers in this field have focused on five main issues: (a) analyzing the environmental performance of different Chinese TSs (b) Repair and maintenance problems of TSs considering environmental factors (c) studying energy efficiency in TSs and identifying weaknesses and potential solution to improve the existing systems (d) surveying the efficiency of TSs by considering and non-considering undesirable outputs and comparing results (e) dynamic environmental efficiency, emission and sustainability analyzing using MI and panel data based DEA models. The first paper has been published by Chan and Sueyoshi (1991). Until 2004, this category was not a favorite category for researchers, but increasing importance of these issues in all industries and countries attracted researchers’ attention. Although in the first decade, number of published papers are not significant, from 2010 the highest growth rate of published papers in each of six considered major categories belongs to environmental issues. Especially researches in this field have focused on energy consumption and emission in TSs.

A lot of researches (almost %30) have focused on Chinese TSs, as one of the largest pollution producer countries in the world. Because the results cannot be extended to other countries, similar researches can be done in other countries. Environmental and sustainability performance of TSs have a high correlation with energy consumption level. Analyzing the energy consumption problem in TSs and providing practical suggestions to improve the performance is an important research subject. Developing a DEA model for evaluating the TSs using stochastic and random variables can be an interesting research direction. Also, an international study for comparing the under evaluating systems by green and sustainable TSs in order to identify weaknesses and deficiencies could be helpful.

Analyzing the effects of TSs ownership on the sustainability of these systems is another suggestion for future researches. Governments always try to change the performance of existing TSs to better ones, by applying financial and non-financial
policies. Specially they try to reduce emission and improve the sustainability of system. Before any changes, all candidate policies must be evaluated. DEA is a useful tool for this purpose.

5.6. DEA and other transportation researches

In addition to mentioned fields in previous sections, there are some other studies which have focused on the field of DEA applications in TSs. The number of these articles is not high. According to Searching algorithm presented in Section 2, only 86 articles were identified. Based on citation number, rank of journal and novelty of articles, 14 selected papers have reviewed. 53 papers of 86 identified papers have published in last 5 years. Used inputs and outputs in these studies, have presented in Table 5.6.1. Table 5.6.2 presented most cited papers related to DEA applications in environmental issues of TSs. Also, maps of most co-occurrence keywords and co-authorship network have shown in Figure 5.6.1 and Figure 5.6.2, respectively. By using CPM, title, abstract, keywords, references and citations have been surveyed and the evolution and direction of knowledge accumulation in DEA applications in other transportation problems have been shown in Figure 5.6.3. Finally, a review of selected papers has presented in Table 5.6.3.

Based on Figure 5.6.1, the most co-occurrence keywords in the published papers are DEA (data envelopment analysis), public transportation, bus transport, road transport, road safety, urban transit, fundamental analysis. By analyzing this figure, hot research directions in DEA applications in environmental issues of TSs and research gaps can be identified. Investigating co-authorship network presented in Figure 5.6.2 shows a strong relationship between Hermans, Brijs, Shen and Wets who have focused on road safety performance evaluation. Also, Hermans has the most co-authorship with other researchers. Based on Figure 5.6.2, authors who are more to cooperate with other researchers can be identified and the authors can try to cooperate with them in this field. Analyzing the evolution and direction of knowledge accumulation presented in Figure 5.6.3 and searches show that other transportation and DEA researches have focused on eight main issues: (a) Analyzing performance of transportation companies (b) Surveying investment efficiency and transportation projects selection (c) Evaluating efficiency of urban TSs specially bus transportation (d) comparing different TSs (e) Bus lines efficiency (f) Surveying efficiency of transportation networks, supply and demand management in networks (g) Safety in TSs (h) Analyzing the effects of ownership, subsides and etc. on efficiency. Based on data of
54 urban transit companies in France, Kerstens (1996) evaluated technical efficiency of transit companies. This was the first published paper in this category. This work developed by other authors in three different concepts, including urban public TSs evaluation (Costa and Markellos, 1997), investment efficiency and financial problems (Karlaftis, 2003; Rodrigues et al., 2015) and bus industries (Cowie and Asenova, 1999). Although these subjects are still interesting, recently researchers have encountered new challenges. Specially, safety is turned to the most attractive issue since 2011 (Shen et al., 2011).

The trend of recent studies shows safety problem in TSs is one of the most interesting subjects that could be a research direction. Privatization, urban bus transit, subside payment, choosing new facilities, investment and project selection are other interesting research directions.

TSs are known as large systems with a lot of information. Therefore, it will be interesting and challenging to combine big data and data mining techniques by DEA. Data of GIS can be a good data set for such analysis.

Analyzing the performance of transportation vehicles, effects of transportation on housing affordability, and designing and evaluating integrated TSs are newly emerged applications of DEA in TSs.

6. Conclusions and direction for future research

TSs as one of the largest energy consumers and polluter sectors are among the most important and necessary mankind needs. Therefore, evaluating, management and planning TSs is very important. DEA has used widely in performance assessing, studying changes in efficiency, identifying advantages and disadvantages to improve existing systems and etc.

In this paper a literature review and classification of DEA applications in TSs has been presented. First DEA models which have widely used in evaluating performance of TSs, were introduced. Then applications of DEA in the TSs have been studied in six different contexts. More than 600 papers were identified and surveyed and published papers in each context, were analyzed and reviewed deeply. A review of more than 170 selected papers was presented. Comparing the reviewed papers and presented CPMs in six categories shows some interesting facts:
• Based on the CPMs, highway is the oldest category, but articles related to air TSs cover more subjects.

• Analyzing the trend of more than 600 studies shows that about 80% of articles have been published in last 10 years which demonstrate increasing importance of this field over recent years.

• The highest number of published papers is related to air transportation (221 articles), while studies related to the highway TSs have the lowest proportion of studies.

• Although wide range of problems have been studied in each category, the environmental issues are the most important common problems in all categories. In the 90s, and early 21st century, environmental issues were not hot subjects for authors. But by increasing anxiety about the global warming and GHG emission and the significate effects of TSs on these problems, many researchers have been encouraged to consider environmental issues in their studies. More than 59% of environmental related articles have been published in last 5 years and today this topic is the hottest one in DEA applications in TSs.

• It seems that most of environmental articles focus on land TSs (railway and highway TSs).

• Studying the environmental issues, analyzing the effective factors on efficiency e.g. ownership, subsides, population and local factors, efficiency changes during the time and before/after a policy or change, investment and project selection, repair and maintenance are some of the interesting research directions.

We believe that presented taxonomy, review and research gaps in this paper can highlight different research directions for future researches and are an inspiration for new studies in the field of DEA applications in TSs.

**Online Supplement document**

Full list of more than 600 selected published papers on DEA applications in transportation systems is provided in the supplement document.

**References**


Chen, C.C., 2014. The Operation Of New Transportation Infrastructure And Regional Economic Efficiency: A Case Study Of High Speed Rail In Western Taiwan. Regional and Sectoral Economic Studies 14, 179-194.


Table 1. Searching Algorithm to select papers for review.

**Algorithm:**

1. “Transportation” [Article title, Abstract, Keywords]
2. “Highway Transportation” [Article title, Abstract, Keywords]
3. “Airport” [Article title, Abstract, Keywords]
4. “Airline” [Article title, Abstract, Keywords]
5. “Air transportation” [Article title, Abstract, Keywords]
6. “Maritime” [Article title, Abstract, Keywords]
7. “Ports” [Article title, Abstract, Keywords]
8. “Railway Transportation” [Article title, Abstract, Keywords]
9. “Sustainable development” [Article title, Abstract, Keywords]
10. “Eco-design” [Article title, Abstract, Keywords]
11. “Emission” [Article title, Abstract, Keywords]
12. “Data envelopment analysis” [Article title, Abstract, Keywords]
13. “Source Type”: [Journal]
15. “Article Language”: [English]
17. Survey the article title and abstract, full text. Identify and filter related and suitable papers.
18. For section 3: #1 AND #12 AND #13 AND #14 AND #15 AND #16 AND #17
19. For section 5: #2 AND #12 AND #13 AND #14 AND #15 AND #17
20. For section 6: #3 OR #4 OR #5 AND #12 AND #13 AND #14 AND #15 AND #17
21. For section 7: #6 OR #7 AND #12 AND #13 AND #14 AND #15 AND #17
22. For section 8: #8 AND #12 AND #13 AND #14 AND #15 AND #17
23. For section 9: #9 OR #10 OR #11 AND #12 AND #13 AND #14 AND #15 AND #17
24. For section 10: #1 AND #12 AND #13 AND #14 AND #15 AND #17 NOT #2 NOT #3 NOT #4 NOT #5 NOT #6 NOT #7 NOT #8 NOT #9 NOT #10 NOT #11
25. For section 4: Put all identified papers in steps 18-24, in a set
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Model</th>
<th>Transport subject</th>
<th>Ref.</th>
<th>Model</th>
<th>Transport subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rassafi and Vaziri (2007)</td>
<td>BCC</td>
<td>Road, air, Rail, Sea</td>
<td>Cui and Li (2014)</td>
<td>Three-stage virtual frontier DEA</td>
<td></td>
</tr>
<tr>
<td>Sampaio et al. (2008)</td>
<td>BCC</td>
<td>Public transportation</td>
<td>Zhang et al. (2015)</td>
<td>A combined metafrontier approach and DEA, Malmquist index</td>
<td></td>
</tr>
<tr>
<td>Söderberg (2009)</td>
<td>BCC</td>
<td>Public transportation</td>
<td>Wu et al. (2016a)</td>
<td>CCR</td>
<td>Highway</td>
</tr>
<tr>
<td>Savolainen and Hilmola (2009)</td>
<td>CCR</td>
<td>Air transport and railways</td>
<td>Wu et al. (2016b)</td>
<td>CCR/parallel DEA approach</td>
<td></td>
</tr>
<tr>
<td>Michaelides et al. (2009)</td>
<td>CCR</td>
<td>International air transportation</td>
<td>Min and Joo (2016)</td>
<td>CCR</td>
<td>Airlines</td>
</tr>
<tr>
<td>Crujissen et al. (2010)</td>
<td>CCR/BCC</td>
<td>Road transportation</td>
<td>Song et al. (2016)</td>
<td>SBM</td>
<td>Railways</td>
</tr>
<tr>
<td>Sun et al. (2010)</td>
<td>SBM</td>
<td>Urban Public Transportation Terminals</td>
<td>Li et al. (2016)</td>
<td>CCR</td>
<td>Highway</td>
</tr>
<tr>
<td>Novaes et al. (2010)</td>
<td>CCR/BCC</td>
<td>Interstate bus transportation industry</td>
<td>Sun et al. (2016)</td>
<td>Super-efficient DEA</td>
<td></td>
</tr>
<tr>
<td>Wu and Goh (2010)</td>
<td>CCR/BCC</td>
<td>Ports</td>
<td>Azadeh et al. (2016)</td>
<td>BCC</td>
<td>Railway</td>
</tr>
<tr>
<td>Zhao et al. (2011)</td>
<td>NDEA: radial, SBM</td>
<td>Down town space reservation system</td>
<td>Chu et al. (2016)</td>
<td>SBM</td>
<td>Environmental efficiency of transportation</td>
</tr>
<tr>
<td>Chen and Han (2012)</td>
<td>CCR</td>
<td>Regional public transport</td>
<td>Tamaki et al. (2016)</td>
<td>CCR</td>
<td>Urban public transportation</td>
</tr>
<tr>
<td>Su and Rogers (2012)</td>
<td>CCR</td>
<td>National Transportation Systems</td>
<td>Rezaee et al. (2016)</td>
<td>Game-DEA</td>
<td>Urban public transportation</td>
</tr>
<tr>
<td>Chang et al. (2013)</td>
<td>SBM</td>
<td>Regional transport sector</td>
<td>Liu et al. (2017)</td>
<td>SBM</td>
<td>Railway and road</td>
</tr>
<tr>
<td>Vaidya (2014)</td>
<td>CCR</td>
<td>Public urban transportation</td>
<td>Chen et al. (2017)</td>
<td>CCR</td>
<td>Rural transportation</td>
</tr>
<tr>
<td>Chen (2014)</td>
<td>CCR/BCC</td>
<td>Railway</td>
<td>Wang and He (2017)</td>
<td>BCC</td>
<td>Environmental efficiency, provincial transportation system</td>
</tr>
<tr>
<td>Azadi et al. (2014)</td>
<td>Goal-directed two-stage DEA</td>
<td>Chang et al. (2018)</td>
<td>SBM</td>
<td>Environmental efficiency of transportation</td>
<td></td>
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</table>
Table 3. First 30 most cited papers.

<table>
<thead>
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<th>Article</th>
<th>Citation Value</th>
<th>Article</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adler and Golany (2001)</td>
<td>191</td>
<td>Cullinane et al. (2005a)</td>
<td>119</td>
</tr>
<tr>
<td>Sarkis (2000a)</td>
<td>186</td>
<td>Cullinane et al. (2005b)</td>
<td>119</td>
</tr>
<tr>
<td>Martinez-Budria et al. (1999)</td>
<td>147</td>
<td>Azadeh et al. (2008)</td>
<td>101</td>
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</table>

Table 4. Top 13 most active authors.

<table>
<thead>
<tr>
<th>Article</th>
<th>Number of published papers</th>
<th>Article</th>
<th>Number of published papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu, M.M.</td>
<td>19</td>
<td>Merkert, R</td>
<td>8</td>
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<tr>
<td>Barros, C.P.</td>
<td>12</td>
<td>Triantis, K.</td>
<td>8</td>
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<tr>
<td>Wanke, P.</td>
<td>10</td>
<td>Azadeh, A.</td>
<td>7</td>
</tr>
<tr>
<td>Chang, Y.T.</td>
<td>10</td>
<td>Cullinane, K</td>
<td>7</td>
</tr>
<tr>
<td>Wu, J.</td>
<td>10</td>
<td>Odeck, J.</td>
<td>7</td>
</tr>
<tr>
<td>Hilmola, O.P.</td>
<td>9</td>
<td>Lozano, S.</td>
<td>7</td>
</tr>
<tr>
<td>Cook, W.D.</td>
<td>9</td>
<td></td>
<td></td>
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</tbody>
</table>
### Table 5. Most active journals.

<table>
<thead>
<tr>
<th>Section</th>
<th>Journal</th>
<th>Number of published papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway TSs</td>
<td>Accident Analysis And Prevention</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>European Journal Of Operational Research</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Benchmarking / IIE Transactions Institute Of Industrial Engineers / Journal Of Civil Engineering And Management / Journal Of Productivity Analysis / Journal Of Public Procurement / Journal Of The Operational Research Society</td>
<td>2</td>
</tr>
<tr>
<td>Air TSs</td>
<td>Journal Of Air Transport Management</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Transportation Research Part A Policy And Practice</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Transportation Research Part E Logistics And Transportation Review</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>European Journal Of Operational Research / International Journal Of Transport Economics</td>
<td>7</td>
</tr>
<tr>
<td>Maritime TSs</td>
<td>Maritime Economics And Logistics</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Maritime Policy And Management</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Transportation Research Part A Policy And Practice</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>International Journal Of Productivity And Performance Management</td>
<td>2</td>
</tr>
<tr>
<td>Green issues</td>
<td>Transportation Research Part D Transport And Environment</td>
<td>9</td>
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<tr>
<td></td>
<td>Sustainability Switzerland</td>
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<tr>
<td></td>
<td>Journal Of Air Transport Management</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Journal of cleaner production</td>
<td>4</td>
</tr>
<tr>
<td>Other issues</td>
<td>Transportation Research Part A Policy And Practice</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Transportation Research Part E Logistics And Transportation Review</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Socio-Economic Planning Science</td>
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<tr>
<td>Overall</td>
<td>Journal Of Air Transport Management</td>
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<td></td>
<td>Transportation Research Part A Policy And Practice</td>
<td>38</td>
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<td></td>
<td>Maritime Economics And Logistics</td>
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<td>23</td>
</tr>
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<td></td>
<td>International Journal Of Transport Economics</td>
<td>18</td>
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### Table 6. Top countries that have published most papers in DEA applications in TSs.

<table>
<thead>
<tr>
<th>Country</th>
<th>Number of published paper</th>
<th>Country</th>
<th>Number of published paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
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<td>Spain</td>
<td>38</td>
</tr>
<tr>
<td>China</td>
<td>109</td>
<td>United Kingdom</td>
<td>38</td>
</tr>
<tr>
<td>Taiwan</td>
<td>58</td>
<td>Brazil</td>
<td>38</td>
</tr>
<tr>
<td>South Korea</td>
<td>47</td>
<td>Canada</td>
<td>30</td>
</tr>
<tr>
<td>Iran</td>
<td>43</td>
<td>Australia</td>
<td>30</td>
</tr>
</tbody>
</table>
### Table 7. Frequency of the keywords across the DEA and TSs literature.

<table>
<thead>
<tr>
<th>Section</th>
<th>keywords</th>
<th>Frequency</th>
<th>keywords</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Highway TSs</strong></td>
<td>Data Envelopment Analysis</td>
<td>50</td>
<td>Roads And Streets</td>
<td>14</td>
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<tr>
<td></td>
<td>Transportation</td>
<td>18</td>
<td>Decision Making</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>18</td>
<td>Motor Transportation</td>
<td>11</td>
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<tr>
<td><strong>Air TSs</strong></td>
<td>Data Envelopment Analysis</td>
<td>177</td>
<td>Efficiency</td>
<td>62</td>
</tr>
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<td></td>
<td>Air Transportation</td>
<td>83</td>
<td>Airline Industry</td>
<td>54</td>
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<td>Airport</td>
<td>79</td>
<td>Technical Efficiency</td>
<td>45</td>
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<tr>
<td><strong>Maritime TSs</strong></td>
<td>Data Envelopment Analysis</td>
<td>119</td>
<td>Port Operation</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>52</td>
<td>Ports And Harbors</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>DEA</td>
<td>40</td>
<td>Efficiency Measurement</td>
<td>22</td>
</tr>
<tr>
<td><strong>Railway TSs</strong></td>
<td>Data Envelopment Analysis</td>
<td>51</td>
<td>Railway Transport</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>29</td>
<td>Railroad transportation</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Railroads</td>
<td>25</td>
<td>Railways</td>
<td>16</td>
</tr>
<tr>
<td><strong>Green issues</strong></td>
<td>Data Envelopment Analysis</td>
<td>75</td>
<td>China</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td>24</td>
<td>Sustainable development</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>21</td>
<td>Efficiency Measurement</td>
<td>16</td>
</tr>
<tr>
<td><strong>Other issues</strong></td>
<td>Data Envelopment Analysis</td>
<td>73</td>
<td>Decision Making</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>33</td>
<td>Performance Assessment</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>DEA</td>
<td>19</td>
<td>Transportation</td>
<td>13</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td>Data Envelopment Analysis</td>
<td>491</td>
<td>Technical Efficiency</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>193</td>
<td>Air Transportation</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>DEA</td>
<td>114</td>
<td>Airport</td>
<td>79</td>
</tr>
</tbody>
</table>

### Table 8. Most co-cited papers.

<table>
<thead>
<tr>
<th>Article</th>
<th>Co-cited value</th>
<th>Article</th>
<th>Co-cited value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charnes et al. (1978)</td>
<td>159</td>
<td>González and Trujillo (2009)</td>
<td>10</td>
</tr>
<tr>
<td>Banker et al. (1984)</td>
<td>106</td>
<td>Tone (2001)</td>
<td>9</td>
</tr>
<tr>
<td>Pels et al. (2001)</td>
<td>18</td>
<td>Doyle and Green (1994)</td>
<td>8</td>
</tr>
<tr>
<td>Sarkis (2000b)</td>
<td>17</td>
<td>Bazargan and Vasigh (2003)</td>
<td>8</td>
</tr>
<tr>
<td>Debreu (1951)</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. The contribution of different sectors impact on released pollution in the world and USA.

Figure 2. The PRISMA statement for systematic search, reviews and meta-analyses.
Figure 3. Frequency of DEA models used for performance evaluation of TSs.

Figure 4. The contribution of different TSs in published papers.

Figure 5. Annual number of published articles in DEA application in transportation problems.
Figure 6. Annual number of published articles in each section.

Figure 7. Subject area of identified papers in DEA applications in TSs.
Figure 8. Map of most co-occurrence keywords related to DEA applications in transportation.

Figure 9. Map of co-authorship network related to DEA applications in transportation.
Figure 10. Map of most co-cited papers.
Online Supplement document

Online Supplement: Part 1 (List of Tables in each cluster)

Table 5.1.1. Inputs and outputs across the DEA and highway transportation literature.

<table>
<thead>
<tr>
<th>Labour inputs</th>
<th>Capital inputs</th>
<th>Environmental and energy Inputs</th>
<th>Facilities</th>
<th>Other production inputs</th>
<th>Operational Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour inputs: Labor; Number of transportation workers; Number of management, staff and mechanics; Number of ticket agents; Number of management staff; Number of drivers; Number of technicians; Employees; Total manpower.</td>
<td>Capital inputs: Agency cost; Transport Cost; Total expenditure on reseals, rehabilitation general maintenance (contractors costs); Routine Maintenance in dollars; Gross domestic product per capita; Average of construction cost index; Maintenance funding; Fixed assets; Operational costs; Payment to board of governors; Administrative costs; Cost; Asset; Total expenditure; Average pavement condition rating; Government dollars spent via ministry operations; Private consultant dollars spent; Driver cost; Capital investment; Maintenance expenditures; Capital expenditures; safety Highway expenditures; Budget; Construction budget; Highway investment in fixed assets; Private capital; Average total receipts; Average total disbursements;</td>
<td>Environmental and energy Inputs: Transport Risk; Road condition; Gasoline consumption; Diesel consumption; Fuel consumed; Environmental factor; Regional effect variable; Highway network area density; Population density; Average highway network density per person;</td>
<td>Facilities: Freight vehicles; Highway density; Total number of passenger seats; Vehicle per capita; Total urban and rural lane miles; Vehicle-miles traveled; Number of equipment; Number of vehicles; Highway length Passenger vehicles; Framework highway mileage; Total area served; Registered vehicles;</td>
<td>Other production inputs: Safety belt usage; Total Volume Of Cargo Tonnage; Travel Time; Resealing in kilometers; Rehabilitation in kilometers; Quantity of maintenance; Transportation quantity; Public maintenance;</td>
<td>Operational Outputs: Kilometers of highway resealed; Kilometers of highway rehabilitated; General maintenance; Pavement Rating Change Factor; Annual Average Daily Traffic; Length of road; Two-lane equivalent of road; Shoulder width of road; Coefficient for road surface; Coefficient for shoulder; Coefficient for winter operations; Coefficient for other operations; Average time to work in minutes for those not working at home; Estimated number of commuters driving alone/carpool; Average time to work in minutes using mass transit; Estimated number of commuters mass transit; Average score on trucking congestion; Ton miles of truck shipment per state in millions; miles of pavement serviced by a patrol; Fatal crashes; Vehicle-kms; Passenger-kms; Number of passengers; Network length; Assignment size; Average traffic served; Size of system; Average traffic serviced; Reseal length; Rehabilitation length; Level of service; Roughness measures; Production value; Number of lanes; Annual traffic; Change In Overall Bridge Condition; Average Daily Traffic on Interstate bridges per deck area; Average age of bridges; Annual freeze-thaw cycle; Annual precipitation; Passenger capacity; Equivalent sound level; Percentage of new cars; Number of private cars; Average age of private cars; Total number of annual traffic tickets issued for moving violations; Total number of seat belt tickets issued per year; Length of highway; protection of bridges and culverts; Highway transportation output value proportion; Highway cargo transportation capacity; Urbanization rate; Lane-miles Served; Lane km of roadway managed; Volume of shoulder and median repairs and routine maintenance accomplished; Customer satisfaction; Customer coverage rate;</td>
</tr>
</tbody>
</table>
Rapid Response Capability; Roughness measures combined for urban and rural highways; Smooth Travel Exposure; Surface Condition Index; Proportion of Urban to Rural Roads;

**Financial outputs**
Transport revenue; Revenue; Expenditures on Interstate bridge replacement and rehabilitation; Passenger turnover; Freight turnover; Routing expenditure on maintenance; Turnover volume; Expense on salvage; Revenue from helping digging and mending roads; Average GDP per Person; Unit area GDP;

**Environmental and safety outputs**
Accident per vehicle; Injures per vehicle; Fatalities per vehicle; Total cost for all accidents; Number of people severely injured; Number of people with minor injury; Number of pedestrians involved in accidents; Safety; Atmospheric pollution; Greenhouse gas emission; Water pollution; Soil pollution; Accident Prevention Factor; Environmental Difficulty; Number of accidents; Industry pollutant; Change in structurally deficient area; Change in functionally obsolete area; Nitrogen oxides emission; Particulate matter emission; CO\textsubscript{2} emission; Number of drivers involved in injury accidents, involving alcohol/drug violations, by place of residence of the driver; Number of drivers involved in injury accidents involving alcohol/drug violations, by accident location; Numbers of accident sites repaired; Total reduction in accident;

Table 5.1.2. Most cited papers related to DEA applications in highway TSs.

<table>
<thead>
<tr>
<th>Article Citation</th>
<th>Citation Value</th>
<th>Article Citation</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll et al. (1991)</td>
<td>219</td>
<td>Yu (2008b)</td>
<td>26</td>
</tr>
<tr>
<td>Rouse et al. (1997)</td>
<td>44</td>
<td>Yu and Fan (2006)</td>
<td>23</td>
</tr>
<tr>
<td>Nozick et al. (1998)</td>
<td>26</td>
<td>Cook et al. (1991)</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 5.1.3. A review of selected papers across the DEA and highway TSs literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Summary of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kazakov et al. (1989)</td>
<td>Using DEA, relative efficiency of a set of active highway maintenance patrols in Ontario were obtained. This study focused on identifying inputs and outputs to evaluate highway maintenance patrols.</td>
</tr>
<tr>
<td>Cook et al. (1991)</td>
<td>CCR and bounded DEA models were used to evaluating 62 highway maintenance patrols in Ontario. Technical efficiency and management efficiency were obtained and analyzed.</td>
</tr>
<tr>
<td>Rouse et al. (1997)</td>
<td>Considering environmental factors and based on data of 1993-94, performance of 73 highway maintenance patrols in New Zealand were surveyed. Results were analyzed in three respects: Efficiency, Effectiveness and Economy.</td>
</tr>
<tr>
<td>Cook et al. (2001)</td>
<td>Classic CCR and bounded CCR model were used to prioritize 50 highway accident sites considering cost of repair and driver inconvenience factors.</td>
</tr>
<tr>
<td>Rouse and Putterill (2005)</td>
<td>In this study, efficiency and productivity of highways maintenance, before and after structural changes and merger policies was studied. This article focuses on evaluating local governments in New Zealand in 1997-1982. The results showed that merger policies have impact on efficiency scores.</td>
</tr>
<tr>
<td>Wang and Tsai (2009)</td>
<td>Using CCR and BCC models, productive efficiency, technical efficiency, and scale efficiency of 31 highway maintenance sectors which belongs to directorate general of Taiwan highways were obtained. Some short/long term suggestions provided to improve performance.</td>
</tr>
<tr>
<td>Rouse and Chiu</td>
<td>Focusing on local roads in highway systems, 74 Territorial Local Authorities in New Zealand were surveyed. Using DEA, relative efficiency of 74 Territorial Local Authorities were evaluated. The results showed that merger policies have impact on efficiency scores.</td>
</tr>
</tbody>
</table>
New Zealand were analyzed to study how efficient and economical they are. Costs, quantity, quality, and environmental factors, e.g., life-cycle, were considered.

Considering Virginia Department of Transportation as a case study, overall efficiency of highway bridges maintenance, due to environmental and operational factors, was measured. Seven sections in Virginia were evaluated. Based on results, inefficiency causes for each DMU were surveyed.

Using two-stage DEA model and data from Directorate General of Taiwan Highways in 2002, 31 highway maintenance and construction offices were evaluated. SMB was used to identify slacks values. To evaluate highway maintenance, Multi-stage DEA models are better than single-stage models.

Input and output oriented DEA models were applied for prioritizing different bioethanol transportation modes, considering environmental factors. The results help Brazilian government to improve bioethanol TSs, especially highway transportation system.

Using Malmquist index (MI), performance of 50 states of the USA during 2002-2008 was analyzed in order to reduce traffic fatalities. Average productivity of states had a slight decline in reducing fatal crashes. Policies which lead to increased use of seat belts and highway safety were effective.

In this study cost and effectiveness difference between public-private and traditional partnerships in highway construction and delivery projects were studied. Technical efficiency was analyzed for both groups. The results showed that initial cost for public-private partnership projects is higher, while technical efficiencies are not significantly different.

In this paper, DEA was used to compare TSs of Turkey to TSs in EU countries in terms of greenhouse gas emissions. Using renewable energies is a very effective policy for increasing the efficiency of TSs in Turkey.

30 regional TSs in China were analyzed. DEA source reallocation is used for each DMU to maximize minimum satisfaction degree and environmental efficiency.

Sustainability of highway TSs was studied. Three perspectives of sustainability, including social, economic, and environmental, were considered for assessing 30 highway transport systems in Oregon, USA.

Super-efficiency slacks-based measure model was obtained by considering desirable and undesirable outputs, environmental, and energy efficiency of TSs in 30 provinces in China. Highway TSs in China are inefficient in environmental and energy consumption terms.

Efficiency of highway TSs in Beijing-Tianjin-Hebei regions were obtained and analyzed. Results showed that these regions have lower efficiency scores than Yangtze River Delta and Pearl River Delta urban regions. Efficiency score obtained for each region shows that government must apply different appropriate strategies for every region.

By using statistical methods and DEA, considering severity of accidents and decision-making style of driving, effective factors on road accidents were studied based on data of 500 samples in Tehran.

Using parallel SBM model, at first, performance of land TSs was analyzed then, efficiency of highway and railway TSs was obtained separately. Environmental performance of land transport system in East area is better than central and the west areas. Also, the efficiency of railway transportation is more than the highway transportation.
Table 5.2.1. Inputs and outputs across the DEA and air transportation literature.

<table>
<thead>
<tr>
<th>Labour inputs</th>
<th>Number of employees; Number of core business workers; Labor; Managerial; Engineers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital inputs</td>
<td>Labor, capital and materials expenditures; Staff costs; Operating costs; Total economic cost; Operating expense less employee expenditure; Maintenance costs; Soft costs; Maintain Expense; Operating expenses; Capital stock; Access cost; Payroll; Employee expenditure/Staff strength; Flight capital; Other operating costs; Outsourcing costs; Total operating cost net of depreciation and amortization costs; Total non-flight assets;</td>
</tr>
<tr>
<td>Environmental and energy inputs</td>
<td>Annual water consumption; Final consumption of electricity; CO₂ emission per capita; Fossil Fuel Energy Consumption; Annual electricity consumption; Petroleum gas consumption; Gallons of jet fuel; Annual liquefied; Fuel;</td>
</tr>
<tr>
<td>Facilities</td>
<td>Number of runways; Number of gates; Terminal area; Total runway area; Route; Number of vehicle parking spaces; Baggage claim area; Distance to nearest city center; Number of baggage collection belts; Number of public parking spots; Available seat kilometers; Terminal capacity; Runway capacity; Apron capacity; Security capacity; Number of planes; Dimension of runway unit; Passenger terminal area; Airport Surface; Number Of Parking Slots; Available ton kilometer which reflects aircraft capacity; Number of operated aircraft; Runway length; Apron size; Airport ramp; Baggage handling capacity; Snow removal equipment; Fire truck &amp; stations; Hangers; Departure lounge; Number of check-in counters; Curb frontage; Number of boarding gages;</td>
</tr>
<tr>
<td>Other production inputs</td>
<td>Outsourcing; Ratio of flight stage miles to trip stage miles; Maintenance; Cleaning; Security; Underutilization (in percentage);</td>
</tr>
<tr>
<td>Operational Outputs</td>
<td>Passengers; Air traffic movements; Tons of cargo; Number of residents who can get the airport by car in 90 minutes; Peak hour movements; Aircraft movements; Service rating; Available seat kilometres; Number of planes; Total freight; Annual passenger throughputs; Annual Number of flights; Annual cargo throughputs; Non-weather related delays; Commuter movements; Domestic passengers, boarded plus disembarked, in thousands; Tons of aviation kerosene; Charter Flights; Domestic passengers; Air transport movements;</td>
</tr>
<tr>
<td>Financial outputs</td>
<td>Commercial revenues; Returns from infrastructure services; Total returns; Operative returns; Final returns; Net Profit/loss; Revenue passenger kilometer; Non-passenger revenue at current prices; Operating revenue; General aviation; Non-aeronautical revenue; Earnings before interest and taxes; Duty free and retail revenues; Catering revenues; Car parking revenues; Rental revenues; Banking revenues; Entertainment revenues; Passenger services revenues; Airport cities revenues; Aircraft landing fees; Passenger charges &amp; fees; Aircraft parking fees; Ground handling fees; Cargo fees; Centralized infrastructure fees; Aeronautical revenues; Non-aeronautical revenues; Aeronautical receipts; Handling receipts; Commercial receipts;</td>
</tr>
<tr>
<td>Environmental and safety outputs</td>
<td>CO₂ emission volume; Environmental &amp; Noise surcharges; Security charges; Aircraft noise; Air pollution;</td>
</tr>
</tbody>
</table>
Table 5.2.2. Most cited papers related to DEA applications in air TSs.

<table>
<thead>
<tr>
<th>Article</th>
<th>Citation Value</th>
<th>Article</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarkis (2000a)</td>
<td>186</td>
<td>Bazargan and Vasigh (2003)</td>
<td>114</td>
</tr>
<tr>
<td>Pels et al. (2003)</td>
<td>155</td>
<td>Merkert and Hensher (2011)</td>
<td>100</td>
</tr>
<tr>
<td>Parker (1999)</td>
<td>146</td>
<td>Barbot et al. (2008)</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 5.2.3. A review of selected papers across DEA and air TSs literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Summary of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schefczyk (1993)</td>
<td>15 international airports were analyzed based on data of 1989-1992. Standard DEA was used. The results showed that operational efficiency, marketing performance and resource acquisition are key factors for high profitability.</td>
</tr>
<tr>
<td>Charnes et al. (1996)</td>
<td>Operational efficiency for domestic and international activities of airlines in Latin America in 1988 was surveyed.</td>
</tr>
<tr>
<td>Gillen and Lall (1997)</td>
<td>Considering data of 21 airports in USA during 1989-1993, effects of an airport manager’s decision on efficiency and performance of airport were studied. DEA and Tobit regression were applied to identify managing strategies to improve efficiency scores in terminals and airsides.</td>
</tr>
<tr>
<td>Sengupta (1999)</td>
<td>Dynamic DEA model was used to survey trend of efficiency changes in 14 international airports from 1988 to 1994. The results showed the significant changes in efficiency scores.</td>
</tr>
<tr>
<td>Sarkis (2000b)</td>
<td>Results of evaluating 44 major American airports showed that the average of airports efficiency was increased.</td>
</tr>
<tr>
<td>Martin and Roman (2001)</td>
<td>To investigate privatization effects on capacity constraints at European airports, 37 Spanish airports were evaluated. Privatization and partnership with private sector can improve efficiency of airports.</td>
</tr>
<tr>
<td>Pels et al. (2001)</td>
<td>Relative efficiency of 34 European airports during 1995-1997 was calculated by DEA. Most airports were inefficient. There is a significant difference between performances of different airports.</td>
</tr>
<tr>
<td>Adler and Golany (2001)</td>
<td>Using an integrated DEA and principal component analysis (PCA), performance of deregulated airline networks in west Europe was studied.</td>
</tr>
<tr>
<td>Adler and Berechman (2001)</td>
<td>Using DEA and PCA relative efficiency and quality of European and non-European airports were analyzed. Airports quality is an effective factor in selection of hubs by airlines.</td>
</tr>
<tr>
<td>Fernandes and Pacheco (2002)</td>
<td>BCC DEA model was applied to evaluate capacity and productivity of 35 Brazilian domestic airports which are investigated in terms of number of</td>
</tr>
</tbody>
</table>
serviced passengers. Slacks values were identified.

**Pels et al. (2003)** Based on data from 34 European airports, efficiency were obtained and analyzed. The results showed that European airports are inefficient, on average. Airlines inefficiency is significantly affected by airports inefficiency in passenger transportation.

**Pacheco and Fernandes (2003)** Standard DEA and MI were applied to evaluate performance of 16 European airlines between 1977 and 1990. The results indicated significant slacks values in East regions versus West Regions.

**Bazargan and Vasigh (2003)** Performance of 45 American commercial airports in three groups including large, medium and small size, was evaluated. The results showed small airports had the highest efficiency scores.

**Sarkis and Talluri (2003)** Using DEA, performance of 44 major airports in USA from 1990 to 1994 was evaluated. Some strategies were suggested to improve overall performance.

**Scheraga (2004)** Standard DEA and regression analyzes were applied to evaluate performance of 38 international airlines. Passenger service costs have negative effect on efficiency when marketing costs have positive effect.

**Tsikriktsis and Heineke (2004)** Efficiency of 10 American airlines in 1987-1998 was analyzed by using standard DEA and time series regression.

**Capobianco and Fernandes (2004)** This study evaluated 53 international airlines during 1993-1997. Standard DEA model was used for this research. Performance of airlines highly depends on their management. Major airline companies were more efficient in using their capital for profitability.

**Yoshida and Fujimoto (2004)** Based on data of 2000, 67 Japanese airports were evaluated. Effects of overinvestment on efficiency scores were analyzed.

**Yu (2004)** Considering environmental factors and undesirable outputs, physical efficiency of 14 domestic Taiwan’s airports was obtained during 1994-2000.

**Chiou and Chen (2006)** Performance of 15 Taiwan’s airlines in 2001 was evaluated using standard DEA and Tobit regression.

**Lin and Hong (2006)** Operational efficiency of 20 international major airports around the world were assessed. The results showed that economic growth rate of the country which airport is located in, hub airports and airport geographical location are affective factors for operational efficiency of the airport.

**Barros and Dieke (2007)** Operational and financial efficiency of Italian airports was evaluated during 2001-2003 using panel data based DEA model.

**Greer (2008)** Using standard DEA model and MI, performance of 8 American airlines from 2000 to 2004 was evaluated. An increase in efficiency of energy consumption, labor and available seat-mile capacity was observed.

**Barbot et al. (2008)** Based on data of 49 international airlines in 2005 total productivity was obtained by using standard DEA model. Results showed that the efficiency of airlines depends on geographical location.

**Yu et al. (2008)** Considering aircraft noise and using MI, changes in efficiency of 4 major Taiwan’s domestic airports from 2001 to 2005 was analyzed.


**Barros and Dieke (2008)** Based on data during 2001-2003 and using a novel two-stage model, technical efficiency of Italian airports was analyzed. Due to efficient frontier, weakness
points of airports with low efficiency identified and some suggestions were proposed to improve current situation.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lam et al. (2009)</td>
<td>Operational performance of 11 Asia-Pacific airports from 2001 to 2005 was assessed.</td>
</tr>
<tr>
<td>Greer (2009)</td>
<td>During a 10-year period from 1999 to 2008, using standard DEA and Tobit regression, efficiency of 17 major American airlines was evaluated. Results showed that labor unions don’t affect efficiency.</td>
</tr>
<tr>
<td>Bhadra (2009)</td>
<td>Standard DEA was used to evaluate performance of 13 American airlines during 1985-2006. By reducing block time, efficiency of airlines will increase.</td>
</tr>
<tr>
<td>Chi-Lok and Zhang (2009)</td>
<td>Based on data of 1996-2006, 25 major Chinese airports were evaluated. Effects of policies and reforms in TSs on airports efficiency were analyzed. Results showed that localization of airports have significant effect on efficiency scores.</td>
</tr>
<tr>
<td>Curi et al. (2010)</td>
<td>Using DEA, effects of Italian government strategies including privatization, developing airport management services and establishment of two new hubs on productivity of 36 airports were analyzed in 2001 and 2003. Results showed that new hubs are inefficient sources.</td>
</tr>
<tr>
<td>Ouellette et al. (2010)</td>
<td>In a 40-year period from 1960 to 1999, performance of 7 Canadian airlines was evaluated using standard DEA model. Changes in regulation and deregulation are the main reasons of inefficiencies.</td>
</tr>
<tr>
<td>Merkert and Hensher (2011)</td>
<td>The impact of strategic management and fleet planning on airlines efficiency were investigated. A two-stage DEA model applied to data of 58 airline passengers from 2007 to 2009. Results showed that fleet have not a significant impact on technical efficiency but it affects allocative and cost efficiency positively.</td>
</tr>
<tr>
<td>Assaf and Gillen (2012)</td>
<td>Effects of governmental structure and economical regulation on airports efficiency were analyzed. Analysis of the data from several countries showed that economical regulation affects relative efficiency more than governmental structure.</td>
</tr>
<tr>
<td>Chow and Fung (2012)</td>
<td>To estimate indicators which affect performance of airports, performance of 30 Chinese airports from 2000 to 2006 was investigated by using MI.</td>
</tr>
<tr>
<td>Ha et al. (2013)</td>
<td>To survey market structure of airlines and efficiency of airports, 10 major airports in east Asia were evaluated. DEA and statistical models were applied on data of 1994-2011.</td>
</tr>
<tr>
<td>Chang et al. (2013a)</td>
<td>Performance of 41 Chinese airports in 2008 was evaluated by using DEA and second stage regression.</td>
</tr>
<tr>
<td>De Nicola et al. (2013)</td>
<td>DEA and MI were applied to assess efficiency of 20 Italian management companies during 2006-2008. Results showed that according to infrastructure, performance of airport is acceptable. However, by reducing waiting time and improving management methods, they can increase their productivity.</td>
</tr>
<tr>
<td>Fan et al. (2014)</td>
<td>Using DEA and data of 20 Chinese airports during 2006-2009, regarding to flight delays, performance of airports was evaluated.</td>
</tr>
<tr>
<td>Tsui et al. (2014)</td>
<td>Considering data of 21 airports from 2002 to 2011, operational efficiency of Asia Pacific airports were evaluated.</td>
</tr>
<tr>
<td>Ahn and Min</td>
<td>Performance of 23 international airports in Europe, North America and East Asia was evaluated.</td>
</tr>
</tbody>
</table>
Asia were evaluated during 2006-2011. Classic DEA model and MI were used for this study.

Using a two-stage DEA model, cost efficiency of 35 Italian and 45 Norwegian airports was analyzed during the time. Competition effects on performance were investigated. The results showed that competition level plays an important role in regional and small airports performance.

Bootstrapped DEA model was applied for performance assessing of 48 international airlines during 2007-2010.

Performance of 11 airlines in Middle East in 2010 was evaluated by using DEA network SBM model.

DEA was used to evaluate efficiency of 38 international airlines in 2010.

Performance of 27 international airlines in 2010 was analyzed by using SBM. Energy consumption is one of the main reasons for inefficiencies.

Using Bootstrapped DEA, 42 European and American airports were evaluated in a 5-year period, from 2001 to 2005. Results showed that major airlines which want to be able to compete with other airlines, need to reorganize and resize their operations. Results showed that capital efficiency affects energy efficiency.

Considering CO₂ emission as an output, energy efficiency of 11 airlines during 2008-2012 was evaluated. Financial crisis in the USA has a significant impact on changes in energy efficiency in this period.

To evaluate quality of service and profitability, performance of 30 international airports were investigated by using DEA and second stage regression.

Based on panel data from 2009 to 2013 and by using network DEA, overall and operational efficiency of sub-networks in 10 airports in east Asia was studied.

Operational performance of 21 Turkish airports during 2009-2014 was studied using by MI. Results showed that efficiency of airport was increased during the time.

Using network DEA, allocation efficiency, passenger transportation efficiency and cargo transportation efficiency of 477 Chinese airlines were evaluated. According to efficiency scores obtained from airlines, performance of 82 airports was assessed.

A dynamic network DEA was applied to evaluate performance of 8 Iranian airlines during 2010-2012. Results of presented model compared to existing dynamic and network DEA models results.

For evaluating efficiency and changes in efficiency of airport companies in east Asia countries, a multi-period network DEA model was used. This study planned to survey effects of internal operations of sub-networks and annual operations on airports’ overall efficiency.

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Methodology</th>
<th>Date</th>
<th>Geography</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Merkert and Mangia</td>
<td>Classic DEA model and MI</td>
<td>2006-2011</td>
<td>Asia</td>
<td>Cost efficiency of airports analyzed. Competition level plays important role.</td>
</tr>
<tr>
<td>2014</td>
<td>Tavassoli et al.</td>
<td>DEA network SBM model</td>
<td>2010</td>
<td>Middle East</td>
<td>Performance of airlines evaluated.</td>
</tr>
<tr>
<td>2014</td>
<td>Wu and Liao</td>
<td>DEA</td>
<td>2010</td>
<td>International</td>
<td>Efficiency of airlines analyzed.</td>
</tr>
<tr>
<td>2014</td>
<td>Lee and Worthington</td>
<td>DEA</td>
<td>2010</td>
<td>International</td>
<td>Performance of airlines evaluated.</td>
</tr>
<tr>
<td>2015</td>
<td>Merkert and Assaf</td>
<td>DEA and second stage regression</td>
<td>2010</td>
<td>International</td>
<td>Performance of airports evaluated.</td>
</tr>
<tr>
<td>2016</td>
<td>Liu</td>
<td>Network DEA</td>
<td>2009-2013</td>
<td>East Asia</td>
<td>Overall and operational efficiency of airports evaluated.</td>
</tr>
<tr>
<td>2016</td>
<td>Örkçü et al.</td>
<td>MI</td>
<td>2009-2014</td>
<td>Turkey</td>
<td>Operational efficiency of airports evaluated.</td>
</tr>
<tr>
<td>2016</td>
<td>Shao and Sun</td>
<td>Network DEA</td>
<td>2008-2012</td>
<td>China</td>
<td>Efficiency of airlines evaluated.</td>
</tr>
<tr>
<td>2016</td>
<td>Omrani and Soltanzadeh</td>
<td>Dynamic network DEA</td>
<td>2010-2012</td>
<td>Iran</td>
<td>Performance of airlines evaluated.</td>
</tr>
<tr>
<td>2017</td>
<td>Liu</td>
<td>Multi-period network DEA</td>
<td>2010-2012</td>
<td>East Asia</td>
<td>Efficiency and changes in efficiency of airports evaluated.</td>
</tr>
</tbody>
</table>
Table 5.3.1. Inputs and outputs across DEA, ports and maritime transportation literature.

<table>
<thead>
<tr>
<th>Category</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Labour inputs</strong></td>
<td>Size of labor force; Number of workers; Number of employees; Average age of employees; Indirect labour</td>
<td>Container throughput; Service level; User satisfaction; Ship calls; TEU berth hour; Total number of containers handled per year; Total cargo moved through the docks; Ship working rate; Total tons throughput; Number of containers; Ships; Movement of freight; Gross gauge; Break-bulk cargo; Containerized freight; Solid bulk and liquid bulk; Productivity; Cargo throughput, number of Overall efficiency; Throughput (TEU); Containers loaded and unloaded; Cargo throughput; TEUs handled; Average number of containers handled per hour per ship; Number of passengers; Number of containers with TEU; Number of containers with no TEU; Available equipment; Total equivalent units; Number of vessel arrivals at port; Quantity of goods handled; Time spent operating in port; Service standards; Total cargo handled; Service level; Total tons throughput; Total cargo moved through docks; Terminal length; Terminal area; Port traffic; Aggregate throughput; Loaded shipments; Solid bulk frequency; Container frequency; Outputs Solid bulk throughput; Solid bulk loading hours; Container loading hours;</td>
</tr>
<tr>
<td><strong>Capital inputs</strong></td>
<td>Personnel-related expenses, such as employees’ remuneration; Harbour land, buildings, wharves, docks, waterways, warehouses and funding inputs for other equipment; Operating expenses; Net fixed asset; Depreciation expense; Salaries and wages; Current liabilities; Capital (number of berths, cranes, tugs); Equipment costs; Revenue; Profitability; Average government port charges per container; Labor expenditures; Depreciation charges; Miscellaneous expenditures; Capital (book value of the assets); Annual investment per port; Value of capital invested; Size of operating costs; Marketability;</td>
<td>Profitability; Revenue; Marketability; Total sales; Operating income; Total revenue; Revenue from port activities, e.g. from leasing equipment, and renting commercial buildings and space; Revenue obtained from rental of port facilities; Market share;</td>
</tr>
<tr>
<td><strong>Energy inputs</strong></td>
<td>Amount of energy consumed;</td>
<td>Emissions; Port city population;</td>
</tr>
<tr>
<td><strong>Facilities</strong></td>
<td>Terminal length; Terminal area; Channel width; Channel depth; Maximal quay depth; Solid bulk frequency; Outputs Solid bulk throughput; Port land area; Yard area; Warehousing area; Stocking area; Quay length; Quay cranes; Transfer cranes; Straddle carriers; Reach stackers; Berth length; Cranes; Tugs; Quayside gantry; Straddle carrier; Ship-shore container gantry; Container berth; Number of berths; Parking lot; Total length; Yard gantries; Area of container base; Number of gantry cranes; Length of container terminals; Number of deep-water piers; Container berth length; Containers; Container cranes (number); Mix of 20-foot and 40-foot containers; Size of hard areas; Number of straddle carriers; Amount of yard equipment; Straddle carrier; Cargo throughput, number of ship calls; Berthing capacity, cargo-handling capacity; Land factor; Equipment factor; Uniformity of facilities and cargo;</td>
<td></td>
</tr>
<tr>
<td><strong>Other production inputs</strong></td>
<td>Container frequency; Average idle time; Productivity; Length of delay; Solid in bulk; Liquid in bulk; General commodities; Frequency of ship calls; Average delays in commencing stevedoring; Difference between the berth time and gross working time; Number of containers lifted per quay crane hour; Overall efficiency;</td>
<td></td>
</tr>
<tr>
<td><strong>Operational Outputs</strong></td>
<td>Container throughput; Service level; User satisfaction; Ship calls; TEU berth hour; Total number of containers handled per year; Total cargo moved through the docks; Ship working rate; Total tons throughput; Number of containers; Ships; Movement of freight; Gross gauge; Break-bulk cargo; Containerized freight; Solid bulk and liquid bulk; Productivity; Cargo throughput, number of Overall efficiency; Throughput (TEU); Containers loaded and unloaded; Cargo throughput; TEUs handled; Average number of containers handled per hour per ship; Number of passengers; Number of containers with TEU; Number of containers with no TEU; Available equipment; Total equivalent units; Number of vessel arrivals at port; Quantity of goods handled; Time spent operating in port; Service standards; Total cargo handled; Service level; Total tons throughput; Total cargo moved through docks; Terminal length; Terminal area; Port traffic; Aggregate throughput; Loaded shipments; Solid bulk frequency; Container frequency; Outputs Solid bulk throughput; Solid bulk loading hours; Container loading hours;</td>
<td></td>
</tr>
<tr>
<td><strong>Financial outputs</strong></td>
<td>Profitability; Revenue; Marketability; Total sales; Operating income; Total revenue; Revenue from port activities, e.g. from leasing equipment, and renting commercial buildings and space; Revenue obtained from rental of port facilities; Market share;</td>
<td></td>
</tr>
<tr>
<td><strong>Environmental outputs</strong></td>
<td>Emissions; Port city population;</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.3.2. Most cited papers related to DEA applications in maritime TSs.

<table>
<thead>
<tr>
<th>Article</th>
<th>Citation Value</th>
<th>Article</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tongzon (2001)</td>
<td>312</td>
<td>Cullinane et al. (2005a)</td>
<td>119</td>
</tr>
<tr>
<td>Roll and Hayuth (1993)</td>
<td>192</td>
<td>Zhou et al. (2008)</td>
<td>95</td>
</tr>
<tr>
<td>Martinez-Budria et al. (1999)</td>
<td>147</td>
<td>BARROS (2003)</td>
<td>76</td>
</tr>
<tr>
<td>Turner et al. (2004)</td>
<td>126</td>
<td>Hung et al. (2010)</td>
<td>65</td>
</tr>
<tr>
<td>Cullinane et al. (2005b)</td>
<td>117</td>
<td>Itoh (2002)</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 5.3.3. A review of selected papers across DEA, ports and maritime TSs literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Summary of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll and Hayuth (1993)</td>
<td>Based on data of 20 ports all around the world, port efficiencies were evaluated and analyzed.</td>
</tr>
<tr>
<td>Martinez-Budria et al. (1999)</td>
<td>Relative efficiency of 26 Spanish ports were obtained. This study used a 5-year period data. Based on complexity level, ports were divided in to three categories. Results showed that ports with higher level of complexity have higher efficiency scores.</td>
</tr>
<tr>
<td>Tongzon (2001)</td>
<td>An international comparison was done on performance of 24 Australian and other countries ports. Both of CRS and VRS assumptions were considered in this study.</td>
</tr>
<tr>
<td>Bonilla et al. (2002)</td>
<td>Based on data of 26 Spanish ports, goods traffic efficiency was obtained. Also by using bootstrap analysis, confidence interval was calculated.</td>
</tr>
<tr>
<td>BARROS (2003)</td>
<td>In this study technical efficiency and technology changes in 11 Portuguese sea ports were analyzed based on panel data. The results showed that privatization does not necessarily improve performance of all ports.</td>
</tr>
<tr>
<td>Park and De (2004)</td>
<td>Using DEA and data of 11 Korean ports in 1999, efficiency scores were obtained. CCR and BBC model were used for efficiency calculation and results comparison.</td>
</tr>
<tr>
<td>Barros and Athanassiou (2004)</td>
<td>Based on balanced panel data of 6 Portuguese and Greek ports from 1998 to 2000, performance of ports were assessed and analyzed. By analyzing the results, improving policies for European sea ports were suggested.</td>
</tr>
<tr>
<td>Turner et al. (2004)</td>
<td>Productivity growth of sea ports infrastructure in North America from 1984 to 1997 was studied. Using Tobit regression effective factors on infrastructure efficiency were identified. Relationship between infrastructure efficiency and industry structure were surveyed. The results indicated a strong relationship between railway industry and infrastructure efficiency of container ports.</td>
</tr>
<tr>
<td>Cullinane et al. (2005a)</td>
<td>By using DEA and based on data of 25 major Chinese ports, relationship of privatization and container ports efficiency were studied. This study rejected positive effect of privatization on ports efficiency.</td>
</tr>
<tr>
<td>Cullinane et al. (2005b)</td>
<td>By using DEA and Free Disposal Hull model, Productivity of 30 pioneer container ports and terminals were analyzed in 2001. Results showed that obtaining efficiency scores by panel data, provides better results comparing to cross-sectional data.</td>
</tr>
<tr>
<td>Rios and Maçada (2006)</td>
<td>Using BCC model and data of 15 Brazilian, 6 Argentinian and 2 Uruguay container ports during 2002-2004, relative efficiency of ports was obtained and analyzed.</td>
</tr>
</tbody>
</table>
| Wang and Cullinane (2006)    | Based on data of 104 terminal ports in 29 European countries in 2003, relative efficiency scores were obtained. British ports and ports in west Europe countries have highest level of efficiency. Efficiency in Scandinavian and east
Europe countries is weak.

**Cullinane et al. (2006)** Technical efficiency of 57 major container ports in the world was evaluated using DEA and SFA. Results showed that efficiency scores were strongly dependent on privatization. For making policies, the analysts must use panel data. Because using cross-sectional data has high level of risk.

**Lin and Tseng (2007)** Five different DEA models were applied to assess performance of 10 container ports in Asia-Pacific in 1998. Trend of ports efficiency scores of was analyzed. Slacks values and weaknesses were identified.

**Liu (2008)** Using CCR, BCC and 3-stage DEA models efficiency changes in performance of 10 Asia-Pacific ports from 1998 to 2001 were analyzed. The results showed different models produce different results.

**Pillania et al. (2008)** India's logistics competitiveness and efficiency of Indian terminal ports were studied during 2000-2005. The results showed cargo transportation industry is a competitive industry where transportation industry is not. Also major ports were not efficient.

**Sharma and Yu (2009)** An integrated data mining and DEA method was used to evaluate terminals. A step by step plan was presented to achieve efficient frontier for inefficient terminals. This plan designed based on maximum capacity and input features.

**Lozano (2009)** MI was applied to estimate efficiency changes in Spanish ports from 2002 to 2006. Changes in technical efficiency, technology and scale efficiency were studied in this article.

**Wu and Goh (2010)** Most major ports from 25 selected countries were considered as DMUs. Using DEA and based on data of 2005, operational efficiency in advanced markets and emerging Markets were obtained and results were compared.

**Cullinane and Wang (2010)** Using panel DEA model and data of 25 leading container ports, efficiency scores were obtained during 1992-1999. Results showed significant weakness in ports’ performance. Also slacks values and inefficiency sources were identified.

**Hung et al. (2010)** Operational efficiency, scale efficiency targets and variability of DEA efficiency estimates for 21 container ports in Asia-Pacific were analyzed by using DEA. Selected ports were among 100 leading ports in 2003.

**Bichou (2011)** Operational efficiency of container ports was evaluated using a two-stage supply chain DEA model.

**Lozano et al. (2011)** Considering data of 26 Spanish ports in 2006, application of centralized DEA model in capital budgeting in ports was studied.

**Wanke et al. (2011)** Using DEA and SFA, performance of 25 major Brazilian terminal ports in 2009 was analyzed. The results showed that due to growing economic prosperity and lack of investment in capacity expansion, terminal has limitations in capacity.

**Niavis and Tsekeris (2012)** Standard DEA and Super-efficiency DEA were applied to assess technical efficiency of major sea ports in south east Europe region. The results showed average efficiency score is less than 0.5 which indicates weakness in both management and scale.

**Yuen et al. (2013)** Based on panel data, operational efficiency of terminal ports in China was evaluated from 2003 to 2007. Effects of domestic/foreign ownership and domestic/foreign competition on performance were analyzed. Domestic and foreign competition has positive effects on efficiency.

**Wanke (2013)** Using two-stage network DEA model, performance of 27 Brazilian ports in 2011 was analyzed. The results showed that privatization have positive effects on physical infrastructure efficiency.

**Díaz-Hernández et al. (2014)** Based on data of 27 Spanish ports during 2000-2007 and using Dynamic cost DEA model, efficiency of the ports were obtained. The results of Dynamic
De Oliveira and Cariou (2015) Impacts of competition degree and levels of competition on efficiency of 200 container ports during 2007-2010 were studied. Regional competition has inverse impact on efficiency while the impacts of local and global competition are unclear.

Wanke and Barros (2015) Using two-stage DEA model, efficiency scores of 27 Brazilian ports in 2011 were obtained. This study showed privatization affects physical infrastructures efficiency positively.

Nguyen et al. (2016) Considering data of 43 Vietnamese ports, results of standard DEA, bootstrapped DEA and SFA about performance of ports, were compared. The results showed outputs of all used models are helpful although there is a significant difference between obtained values of each model.

Wanke and Barros (2016) Different DEA models were used to analyze performance of 27 major Brazilian ports during 2007-2011. This study showed that there is a lack of capacity in Brazilian ports. Also performance of ports can be improved by participation of private sector and improving infrastructures.

Cheon et al. (2017) Relationship between environmental and economic performance of 10 top American ports in 2004 was studied. Improvements in physical assets, organizational collaboration and performance monitoring are key factors for improving both aspect of performance.

Mousavizadeh and Khalili-Damghani (2017) Using DEA and artificial neural and based on data of 11 Iranian main ports in 2005, 2010 and 2015, the efficiency scores were obtained. The results showed that when number of DMUs are low and number of inputs and outputs are high, presented method have more discrimination power than standard DEA model.

Chang et al. (2018) Using non-radial SBM DEA models and panel data from 2000 to 2011, the effects of emission control areas on the efficiency of ports in the European Union and North America have been analyzed.

Table 5.4.1. Inputs and outputs across DEA and railway transportation literature.

<table>
<thead>
<tr>
<th>Labour inputs</th>
<th>Labour; Employees; Average annual number of employees;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital inputs</td>
<td>Total expenses and construction budget; Gross national income per capita; Capital; Operating expenditure; Repair and maintenance expenditure; Total annual costs of operation;</td>
</tr>
<tr>
<td>Environmental and energy inputs</td>
<td>Station catchment area population; Fuel; Population density;</td>
</tr>
<tr>
<td>Facilities</td>
<td>Passenger cars; Freight wagons; Passenger coaches; Total routes km; Total locomotives; Number of platforms; percentage of through lines; Total number of cargo cars; Number of containers; Number of yard equipments; Number of handling terminals; Total number of traction vehicles; Materials; Fleet capacity; No. of rolling stock; Locomotives; Track; Freight cars; Engines; Equipment; Gradient; Railcars/EMUs; Total Length of main line; Length of platform; Way and structures;</td>
</tr>
<tr>
<td>Other production inputs</td>
<td>Number of passenger entries and exists; Number of passenger interchanges; Job opportunities in the catchment area; Number of train stops; Transportation density;</td>
</tr>
<tr>
<td>Operational Outputs</td>
<td>Track capacity; Car-miles of shipment of goods; Passenger services; Freight services; Train Km; Passenger train-kms; Freight train-kms; Passenger-kms; Ton-kms; Passenger kilometers per annum; Car kilometers per annum; Externalities on surrounding communities; Total cargo ton transported; Total</td>
</tr>
</tbody>
</table>
Cargotons per kilometers transported; Number of train stops; Railway density;

| Financial outputs | Average salary growth; Passenger revenue; Freight revenue; Revenue ton-mile; Annual total revenues earned; |
| Environmental and safety outputs | Passenger journeys per annum; Accident; CO₂ for railway; Dust; |

### Table 5.4.2. Most cited papers related to DEA applications in railway TSs.

<table>
<thead>
<tr>
<th>Article</th>
<th>Citation Value</th>
<th>Article</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coelli and Perelman (1999a)</td>
<td>278</td>
<td>Growitsch and Wetzel (2009a)</td>
<td>46</td>
</tr>
<tr>
<td>Yu and Lin (2008b)</td>
<td>160</td>
<td>Chapin and Schmidt (1999)</td>
<td>45</td>
</tr>
<tr>
<td>Yu (2008a)</td>
<td>79</td>
<td>Cowie (1999a)</td>
<td>44</td>
</tr>
</tbody>
</table>

### Table 5.4.3. A review of selected papers from DEA and railway TSs literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Summary of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cowie and Riddington (1996)</td>
<td>By considering data of published papers in railways productivity analysis during 1983-1989, railways were reevaluated by using DEA. The results showed that management affects railways efficiency strongly.</td>
</tr>
<tr>
<td>Chapin and Schmidt (1999)</td>
<td>Using panel data of class I railway companies, efficiency of railway companies after deregulation was studied. Analyzing the results showed that deregulation affects efficiency scores but merger has not significant impacts.</td>
</tr>
<tr>
<td>Coelli and Perelman (1999b)</td>
<td>Efficiency of European railways was surveyed and analyzed based on data of 17 companies during 1988-1993.</td>
</tr>
<tr>
<td>Cowie (1999b)</td>
<td>Technical efficiency for public and private ownership in railway industry was investigated by considering Swiss private railway sectors as a case study. Data of 57 small railways including 43 public sectors and 14 private sectors were considered in 1990. The results showed that private sector have a remarkably high level of managerial, organizational and technical performance than public sectors.</td>
</tr>
<tr>
<td>Mbangala Mapapa (2004)</td>
<td>Using standard DEA and MI, performance of railways in sub-Saharan Africa was analyzed. Due to weaknesses in using of resources in production and productivity, most of under study railways are inefficient by average efficiency score of %77.</td>
</tr>
<tr>
<td>Lan and Lin (2005)</td>
<td>For evaluating technical performance of railway TSs, service level, productivity and sale capability growths, four-stage DEA models were used. In this assessing, environmental factors were considered. Data was related to 44 railways around the world during 1995-2001.</td>
</tr>
<tr>
<td>Hilmola (2007)</td>
<td>By considering railways data of 31 European countries during 1980-2003 and using DEA, efficiency of freight railway transportation was studied. Effective factors on demand and efficiency were identified. The results showed that countries that have a high level of performance in the 80s, without exception, have compromising performance. Estonia and Lithuania has the highest efficiency level.</td>
</tr>
<tr>
<td>Authors</td>
<td>Summary</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Yu and Lin (2008a)</td>
<td>To estimate technical efficiency of freight and passenger, service productivity and technical productivity of 20 selected railways in 2002, a multi-activity network DEA model was used. The results showed that obtained values in different criteria were significantly different.</td>
</tr>
<tr>
<td>Yu (2008a)</td>
<td>Network DEA and traditional DEA model were applied to assess technical efficiency, service and technical effectiveness of 40 global railways in 2002. Although obtained values of two used models were different but there were no significant difference in their ranking. Generally network DEA offers better insights about resource inefficiency.</td>
</tr>
<tr>
<td>Graham (2008)</td>
<td>Using DEA and total factor productivity, productivity and efficiency of urban railways were studied. This article considered data of 89 urban railways around the world including underground, light rail, and suburban rail during 1995-1996. The results showed that although obtained values of two used models were different but there were not any significant difference in ranking.</td>
</tr>
<tr>
<td>Jain et al. (2008)</td>
<td>Effects of governmental development models on performance of 15 urban railway systems around the world were investigated during 1992-2002. Among all governmental models, privatization has direct and positive effects on efficiency.</td>
</tr>
<tr>
<td>Growitsch and Wetzel (2009b)</td>
<td>Based on a data set of 54 railways in 27 European countries from 2000 to 2004, using DEA super-efficiency bootstrapping model, effects of vertical integration on railways performance were analyzed.</td>
</tr>
<tr>
<td>Mohajeri and Amin (2010)</td>
<td>By combining DEA and analytical hierarchy process, train stations selection problem in Mashhad was studied. The results showed that obtained weights from AHP can be useful for identifying optimal location of stations as DEA outputs.</td>
</tr>
<tr>
<td>Jitsuzumi and Nakamura (2010)</td>
<td>Based on data of 53 railway companies in Tokyo, Kyushu and Kinki regions during 1998-2003, inefficiency resource were identified. Also optimal level of government’s subsidies is calculated.</td>
</tr>
<tr>
<td>Hilmola (2011)</td>
<td>Using DEA and data of 2000-2004, the impact of geographical location of countries on efficiency of railway transportation is studied. Super efficiency model was applied for performance assessing of freight and passenger railway transportation.</td>
</tr>
<tr>
<td>Shi et al. (2011)</td>
<td>Economical evaluating of productivity growth and technical efficiency of 7 class I American railroads during 2002-2007 was surveyed. MI and sequential DEA models were used. Effective factors on productivity growth in recent years were identified and useful information proposed for policy making.</td>
</tr>
<tr>
<td>Kim et al. (2011)</td>
<td>In this article, modal shift of TSs to railway transportation, as an Eco-friendly system, was studied in Korea. By surveying freight railway transportation and local freight railway transportation features, an alternative plan is provided for green logistics.</td>
</tr>
<tr>
<td>Correa (2012)</td>
<td>Based on data of microeconomic and DEA, land freight TSs including trucking and railway transportation were evaluated. Overall efficiency for railway transportation was more than road transportation efficiency.</td>
</tr>
<tr>
<td>Kutlar et al. (2013)</td>
<td>Performance of 31 rail companies around the world was analyzed during 2000-2009, by using DEA and Tobit regression. Selected companies were doing both freight and passenger transportation. The results showed number of efficient DMUs have increased during the time.</td>
</tr>
<tr>
<td>Noroozzadeh and Sadjadi</td>
<td>Considering safety factors and data of 25 European railways in 2008, efficiency scores were obtained. Number of accidents was considered as undesirable</td>
</tr>
</tbody>
</table>
outputs. Most inefficient DMUs converted to efficient ones by considering safety factors.

Bhanot and Singh (2014) Indexes of business performance of container railway transportation in India, were investigated based on data of three major railway companies during 1995-2011. The results showed that efficiency of private sector is less than other sector.

Rayeni and Saljooghi (2014) Based on a panel data related to Iranian railways from 1977 to 2010, performance of each DMU was evaluated using cross-efficiency measures.


Liu et al. (2016) Energy-environmental efficiency of road and rail TSs in 30 provenances was analyzed using non-radial DEA model in China. The results showed that railway TSs have better performance in both energy and environmental aspects compared to road transportation.

Azadeh et al. (2016a) Using DEA and resilience engineering factors (REF), Tehran–Karaj Electrified Railway system was studied. The results showed that by considering REF, number of efficient DMUs will be increase. Group working has the highest effect on increasing railway systems efficiency.

Sameni et al. (2016) Technical efficiency of 96 most busy passenger stations of railways in Britannia in 2008 was studied, by using a novel assessing and ranking method. According to presented method, trains stops at stations with limited capacity could be managed.

Liu et al. (2017) Based on data of highway and railway TSs in 30 provenances of China during 2009-2012, overall environmental efficiency of land transportation, rail transportation and highway transportation were obtained. Parallel SBM DEA model was used for this study. The results showed environmental efficiency in east areas is higher than central and west areas. Also performance of railway TSs is better than highway TSs.

Zhou and Hu (2017) Using two-stage network DEA model and considering undesirable outputs, sustainable development of Chinese railway TSs was studied during 2002-2013. This article surveyed the railway TSs in economic, social and environmental aspects. The results showed that sustainability in east area is much more than center and west area.

Djordjević et al. (2018) Non-radial DEA model was used to survey safety at railway level crossings in European countries from 2010 to 2012 and in 2014. Desirable and undesirable outputs have been considered in this study.

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</thead>
<tbody>
<tr>
<td>outputs. Most inefficient DMUs converted to efficient ones by considering safety factors.</td>
<td>Indexes of business performance of container railway transportation in India, were investigated based on data of three major railway companies during 1995-2011. The results showed that efficiency of private sector is less than other sector.</td>
<td>Based on a panel data related to Iranian railways from 1977 to 2010, performance of each DMU was evaluated using cross-efficiency measures.</td>
<td>A novel network DEA model was presented to evaluate performance of 13 Iranian railways in 2012. Presented model measures overall efficiency, technical efficiency of freight and passenger transportation, service effectiveness and technical effectiveness, simultaneously.</td>
<td>Energy-environmental efficiency of road and rail TSs in 30 provenances was analyzed using non-radial DEA model in China. The results showed that railway TSs have better performance in both energy and environmental aspects compared to road transportation.</td>
<td>Using DEA and resilience engineering factors (REF), Tehran–Karaj Electrified Railway system was studied. The results showed that by considering REF, number of efficient DMUs will be increase. Group working has the highest effect on increasing railway systems efficiency.</td>
<td>Technical efficiency of 96 most busy passenger stations of railways in Britannia in 2008 was studied, by using a novel assessing and ranking method. According to presented method, trains stops at stations with limited capacity could be managed.</td>
<td>Based on data of highway and railway TSs in 30 provenances of China during 2009-2012, overall environmental efficiency of land transportation, rail transportation and highway transportation were obtained. Parallel SBM DEA model was used for this study. The results showed environmental efficiency in east areas is higher than central and west areas. Also performance of railway TSs is better than highway TSs.</td>
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</tbody>
</table>

Table 5.5.1. Inputs and outputs across the DEA and environmental issues of transportation literature.

<table>
<thead>
<tr>
<th>Labour inputs</th>
<th>Capital inputs</th>
<th>Environmental and energy inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of full time employees; labor hours; Civilian transport employment;</td>
<td>Costs of Pavement maintenance; Costs of Preventative maintenance; Costs of Major drainage; Costs of thin asphalt; Maintenance chip seals; Costs of Seal widening; Costs of area-wide pavement; Costs of Pavement smoothing; Operational costs; Land take by road infrastructure;</td>
<td>Population; Fuel consumption; CO₂ emissions; Coal; Gasoline; Kerosene; Diesel oil; Electricity; Environmental Difficulty;</td>
</tr>
</tbody>
</table>
Facilities
- Runway area; Apron area; Terminal area; Route; Number of aircraft; Highway Mileage; Passenger Seats; Vehicle seats;

Other production inputs
- Vehicle-Kilometer (VKM) traveled by private mode; VKM traveled by transit; VKM traveled by truck; Ton-Kilometer traveled by truck; Vehicle Kilometers Travelled; Modal share by transit; Proportion of Urban to Rural Roads; Routine Maintenance; Resealing in kilometers; Rehabilitation in kilometers;

Operational Outputs
- Movements; Passengers; Passenger-miles; Vehicle-miles; Smooth Travel Exposure; Surface Condition Index; Modal share by transit; Vehicle-Kilometer (VKM) traveled by private mode; VKM traveled by transit; VKM traveled by truck; Ton-Kilometer traveled by truck;

Financial outputs
- Value-Added; Gross product; Passenger Turnover Volume; Freight Turnover Volume; Gross value added from transport;

Environmental and safety outputs
- CO₂ emissions; Alternative energy; Emissions; Aircraft noise; Vehicles recycling; Tires recycling;

Table 5.5.2. Most cited papers related to DEA and environmental issues of TSs.

<table>
<thead>
<tr>
<th>Article</th>
<th>Citation Value</th>
<th>Article</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chang et al. (2013b)</td>
<td>112</td>
<td>Curi et al. (2011)</td>
<td>52</td>
</tr>
<tr>
<td>Sheth et al. (2007)</td>
<td>75</td>
<td>Zhang and Wei (2015)</td>
<td>45</td>
</tr>
<tr>
<td>Chang et al. (2014)</td>
<td>63</td>
<td>McMullen and Noh (2007)</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 5.5.3. A review of selected papers across the DEA and environmental issues of TSs literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Summary of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu (2004)</td>
<td>Based on data of 14 domestic airports in Taiwan during 1994-2000 and considering undesirable outputs and environmental factors, efficiency was studied. Results showed that airports can improve their performance by optimal using of resources and they don’t need to develop their equipment.</td>
</tr>
<tr>
<td>Ramanathan (2005)</td>
<td>Energy efficiency and emissions in railway and road TSs in India has been studied based on data of 1980-1994. Results showed that if %50 of land transportation is railway transportation, %35 of energy consumption will decrease.</td>
</tr>
<tr>
<td>McMullen and Noh (2007)</td>
<td>Based on data of 2000 and considering environmental factors, efficiency of 43 American bus transit agencies was evaluated. When environmental factor have not been considered, only 5 agencies are efficient but without considering these factors 22 agencies are efficient. Private agencies had better performance.</td>
</tr>
<tr>
<td>Rouse and Chiu (2009)</td>
<td>Based on data of 73 Territorial Local Authorities in New Zealand and time period 1994-2003, repair and maintenance of local roads in highways have been studied. Quantity, quality, cost and environmental criteria for efficiency, productivity and economic performance of each DMU have been considered.</td>
</tr>
<tr>
<td>Shiau and Jhang (2010)</td>
<td>Sustainability of transportations systems in Taiwan has evaluated by using DEA and rough set theory. This study considered data belong to 1993-2007. Cost efficiency, cost effectiveness, service effectiveness, service reduction and service impact are considered as five sustainability indicators. Results showed that cost efficiency and service reduction are the most effective factors on sustainability.</td>
</tr>
<tr>
<td>Su and Rogers</td>
<td>Considering economic and environmental factors, efficiency of TSs in OECD countries was analyzed. Data of 2000, 2005 and 2007 was used for this research.</td>
</tr>
</tbody>
</table>
The results indicate a strong relationship between economic efficiency and environmental performance. Based on data of 30 Chinese administrative regions during 2004-2010 and considering undesirable outputs, performance of transportation sectors was evaluated. East region had better performance, while undesirable outputs were considered. But by considering desirable and undesirable outputs simultaneously, efficiency of central region was higher than other regions. Using non-radial DEA model with SBM and data of 30 provinces in mainland of China in 2010, environmental efficiency of transportation sector was studied. Results showed most of provinces had weak environmental efficiency scores (less than 50%).

Technical efficiency of 12 Chinese and non-Chinese airports during 2006-2010 were evaluated. Salary level has positive impact on operational efficiency while international focus has negative impact. Based on data of 30 provinces in mainland of China during 2006-2010, economic and environmental efficiency of 27 airlines around the world were analyzed in 2010. Asian airports were identified as most efficient DMUs. Weakness in fuel consumption was recognized as the main cause of inefficiency.

Dynamic trend of CO$_2$ emission of TSs in 30 provinces in mainland of China from 2002 to 2010 was studied by MI. The results show that weakness in technology leads to weak environmental performance in transportation industry. Using super efficiency SBM and window DEA models, sustainable development, energy consumption and environmental efficiency of 30 provinces in mainland of China from 2011 to 2012, were studied. For improving the performance, surplus and slacks values were identified. Considering data of 30 provinces in mainland of China in 2012, environmental performance and energy consumption of TSs were evaluated. Parallel DEA model was used for analyzing the sustainable development. Most of DMUs had weak efficiency scores. East areas have better performance.

The non-radial DEA model and window analysis were applied to studying energy and environmental efficiency in rail and road transportation in 30 provinces in China from 1998 to 2012. Using Tobit regression, influencing factors on productivity are investigated. East areas had better performance in road transportation, while in railway transportation west areas were better.

This study proposed a directional distance function model for evaluating productivity, economical efficiency and CO$_2$ emissions efficiency. The proposed model was used for evaluating Chinese TSs during 2007-2012. The results showed that economic performance is far greater than environmental performance.

Considering data of 30 provinces in China from 2009 to 2012 and using parallel SBM model, a time/region analysis of Chinese TSs was provided. Environmental factors were considered. Results showed that eastern regions have better performance compared to other areas and rail transportation have better performance compared to road transportation.

| Table 5.6.1. Inputs and outputs across DEA applications in other transportation problems. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Inputs** | Vehicles; Employees; Fuel; Fleet; Workhorse; Passenger kilometers; Numbers of buses operated; effective driving hours; Equipment; Cost; Transfer area; Operating expense; Number of staff in terminal; Capacity of Bus; Infrastructure cost; Travel | | | |
Table 5.6.2. Most cited papers related to DEA applications in other transportation problems.

<table>
<thead>
<tr>
<th>Article</th>
<th>Citation Value</th>
<th>Article</th>
<th>Citation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerstens (1996)</td>
<td>102</td>
<td>Jafari Songhori et al. (2011)</td>
<td>46</td>
</tr>
<tr>
<td>Odeck and Alkadi (2001)</td>
<td>65</td>
<td>Zhao et al. (2011)</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 5.6.3. A review of selected papers across DEA applications in other transportation problems.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Summary of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerstens (1996)</td>
<td>Based on data of 54 urban transit companies in France technical efficiency was obtained and analyzed in 1990. The results showed that subsides have negative effects on efficiency.</td>
</tr>
<tr>
<td>Cowie and Asenova (1999)</td>
<td>Effect of privatization on British bus industry was evaluated using DEA. Data of 1995-96 was used. Private companies have higher efficiency. Small companies have an increasing efficiency trend.</td>
</tr>
<tr>
<td>Odeck and Alkadi (2001)</td>
<td>Data of 47 bus transit companies, which receive subsidy from the government was used for evaluating Norwegian bus transit systems in 1994. Effects of ownership form and operation region on efficiency scores were studied. Ownership form has not any direct effects on efficiency.</td>
</tr>
<tr>
<td>Boame (2004)</td>
<td>Using bootstrap DEA model and based on data of 30 selected systems during 1990-1998, technical efficiency of urban transit systems in Canada was obtained. An increasing efficiency trend was observed. Efficiency mean was %78.</td>
</tr>
<tr>
<td>Odeck (2006)</td>
<td>Effective factors on operational efficiency of Norwegian bus transit industries were studied. Data of 33 companies in 1994 was used. High operational costs are one of the main inefficiency reasons. Ownership form has not any effect.</td>
</tr>
<tr>
<td>Odeck (2008)</td>
<td>Considering data of 17 companies in pre-merger period (1995-1998) and 10 companies in post-merger period (1999-2002), the effect of mergers on Norwegian bus transit industries, was studied. Merging has positive effect.</td>
</tr>
<tr>
<td>Sun et al. (2010)</td>
<td>Transportation efficiency of urban public transit terminals based on data of 10 urban terminals in Beijing in 2008 was studied. Potential opportunities for improving performance were identified.</td>
</tr>
<tr>
<td>Zhao et al. (2011)</td>
<td>Network DEA model used for demand management in transportation networks. This study has surveyed transportation networks from service providers, users and society perspectives. Results showed that improving efficiency of nodes can lead to high efficiency in network.</td>
</tr>
<tr>
<td>Chen et al. (2012)</td>
<td>Using integer DEA model, considering safety records and data during 1994-2009, operational efficiency of Kaohsiung city bus systems was evaluated.</td>
</tr>
<tr>
<td>Behnood et al. (2014)</td>
<td>Road safety performance in 30 Iranian provinces based on data of the years 2008-2009 was studied. Indicators that cause inefficiency in the performance of each province have been identified, then some suggestions provided for improvement.</td>
</tr>
</tbody>
</table>
| Guo et al. (2015)       | Investment efficiency in transportation projects was analyzed. 13 selected
projects were analyzed from technological efficiency, pure technological efficiency and scale efficiency perspectives.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Methodology</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun et al. (2016)</td>
<td>Using AHP and super-efficiency model and based on GIS data, 18 bus transit lines in Shenzhen were evaluated. This study analyzed efficiency scores in view of transit planning, operation and quality of service.</td>
<td></td>
</tr>
<tr>
<td>Wei et al. (2017)</td>
<td>By combining DEA, Geographic Information System, and multi-objective spatial optimization, a new approach has been developed for evaluating public transit services for operational efficiency and access equity. The proposed approach has been applied to public transit services of Wasatch Front, Utah.</td>
<td></td>
</tr>
</tbody>
</table>
References


Martín, J.C., Reggiani, A., 2007. Recent methodological developments to measure spatial interaction: Synthetic accessibility indices applied to high-speed train investments. Transport Reviews 27, 551-571.


Online Supplement: Part 2 (List of Figures in each cluster)

Figure 5.1.1. Map of most co-occurrence keywords related to DEA applications in highway transportation
Figure 5.1.2. Map of co-authorship network related to DEA applications in highway TSs
Figure 5.5.3. CPM of development of DEA applications in highway TSs.
Figure 5.2.1. Map of most co-occurrence keywords related to DEA applications in air TSs
Figure 5.2.2. Map of co-authorship network related to DEA applications in air TSs
Figure 5.2.3. CPM of development of DEA applications in air TSs.
Figure 5.3.1. Map of most co-occurrence keywords related to DEA applications in maritime TSs.
Figure 5.3.2. Map of co-authorship network related to DEA applications in maritime TSs
Figure 5.3.3. CPM of development of DEA applications in maritime TSs.
Figure 5.4.1. Map of most co-occurrence keywords related to DEA applications in railway TSs
Figure 5.4.2. Map of co-authorship network related to DEA applications in railway TSs
Figure 5.4.3. CPM of development of DEA applications in railway TSs.
Figure 5.5.1. Map of most co-occurrence keywords related to DEA and environmental issues of TSs

Figure 5.5.2. Map of co-authorship network related to DEA and environmental issues of TSs
Figure 5.5.3. CPM of development of DEA applications in environmental issues in TSs.
Figure 5.6.1. Map of most co-occurrence keywords related to DEA applications in other transportation problems.
Figure 5.6.2. Map of co-authorship network related to DEA applications in other transportation problems.
Figure 5.6.3. CPM of development of DEA applications in other transportation problems.
Online Supplement: Part 3 (DEA publications in each cluster)

DEA publications: highway transportation system


18. do Castelo Gouveia, M. & Clímaco, I. 2018, Assessment of fuel tax policies to tackle carbon emissions from road transport—an application of the value-based DEA method including robustness analysis.


DEA publications: air transportation system


**DEA publications: maritime transportation system**


415. Wang, Y.-. & Han, T.-. 2018, "Efficiency measurement for international container ports of Taiwan and surrounding areas by fuzzy data envelopment analysis", Journal of Marine Science and Technology (Taiwan), vol. 26, no. 2, pp. 185-193.


**DEA publications: railway transportation system**


474. Kleinová, E. 2016, "Does liberalization of the railway industry lead to higher technical effectiveness?", Journal of Rail Transport Planning and Management, vol. 6, no. 1, pp. 67-76.
486. Martín, J.C. & Reggiani, A. 2007, "Recent methodological developments to measure spatial interaction: Synthetic accessibility indices applied to high-speed train investments", Transport Reviews; vol. 27, no. 5, pp. 551-571.


**DEA publications: sustainability development and green issues in transportation**


537. do Castelo Gouveia, M. & Clímaco, I. 2018, Assessment of fuel tax policies to tackle carbon emissions from road transport—an application of the value-based DEA method including robustness analysis.


593. Yang, C.-. 2012, "Productivity changes in Taiwan's port industry incorporating environmental regulations on harbor water quality", Transportation Planning and Technology, vol. 35, no. 8, pp. 769-789.


**DEA and other transportation researches**


- Present full review of Data Envelopment Analysis approach in transportation systems
- Cluster and provide full analysis of DEA papers in transportation systems
- Propose subjects for future researches in the area of DEA applications in transportation systems
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