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Dynamic performance assessment of bus transit with the multi-activity network structure

Ming-Miin Yu [a], Li-Hsueh Chen [a,*], Bo Hsiao [b]

[a] Department of Transportation Science, National Taiwan Ocean University, No. 2 Pei-Ning Road, Keelung 20224, Taiwan
[b] Department of Information Management, Chang Jung Christian University, No. 1 Changda Road, Gueiren District, Tainan City 71101, Taiwan

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ABSTRACT

This paper proposes a multi-activity dynamic network data envelopment analysis model that combines the multi-activity, network and dynamic DEA models to assess the performance in terms of individual activities, individual processes, individual periods and overall operation. The main advantage of this model is that the linkages among activities and processes, the shared inputs among activities and processes, and the carry-over items among periods are included in a unified model. It can provide more appropriate performance measures. An empirical application of 20 bus transit firms in Taiwan for the period 2004–2012 is provided. Based on the operational characteristics of bus transit firms, both desirable and undesirable outputs are also incorporated into this model. The results show that none of the bus transit firms was effective in terms of the operational effectiveness, and the sources of operational ineffectiveness among bus transit firms were different. Over the period 2004–2012, the period-operational effectiveness scores maintained stable variance, the period efficiencies of highway and urban bus services appeared to have similar patterns, and transit bus firms performed well in the consumption process.

1. Introduction

Bus transit systems play an important role in the regional development of a country. Hence, the issue of bus transit performance is of widespread concern. Traditionally, partial indicators are used to measure the operational performance (e.g., average vehicle-miles per vehicle). However, partial indicators only focus on single or parts of operational factors. They may lead to misleading results in the bus transit industry, because bus transit operations are characterized by multiple inputs and multi-product capability [28]. Performance measurement based on the conventional data envelopment analysis (DEA) model, which aggregates multiple inputs and multiple outputs, can overcome the weakness of partial indicators. The extant literature on performance measurement for bus transit firms has evaluated efficiency by using the conventional DEA model (e.g., [5,26,32,33,9,27,28]).

In Taiwan, a bus transit firm primarily operates two activities: highway bus (HB) service and urban bus (UB) service. Services provided by bus transit firms are unstorable and must be consumed immediately. If they are not consumed, they will disappear [29]. The quantities of consumed service may be a proportion of the quantities of produced service. Hence, the operation of a bus transit firm further involves two processes: production process and consumption process. When bus transit performance is estimated, these unique characteristics of bus transit services should be reflected in the difference between the concepts of efficiency and effectiveness [19]. Efficiency represents “do things right” and is measured by production efficiency (PE), which describes the ratio of actual outputs produced to inputs, while effectiveness represents “do the right things” and is measured by service effectiveness (SEV), which describes the ratio of consumed outputs to produced outputs, and operational effectiveness (OEV), which is the combination of PE and SEV [35]. Since a bus transit firm includes multiple activities and multiple processes, parts of its resources belong to the specific activity or process, while others are shared among different activities and/or processes (e.g., management staff). Furthermore, when bus transit operators plan operationally, they will consider the inter-relationship between consecutive terms, and reserve a proportion of outputs or revenue to the next period (e.g., network length). Hence, in order to understand the operational performance for a bus transit firm, the allocation of shared inputs and the effect of carry-over items between two consecutive terms also need to be taken into account.

Conventional DEA models treat the operational process as a “black box”, and use aggregate data to evaluate efficiency, without considering the linking items in parallel and in series, the

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* Corresponding author. Tel.: +886 2 24622192x7052; fax: +886 2 24633745.
E-mail addresses: yumm@mail.ntou.edu.tw (M.-M. Yu), yoannachen@gmail.com (L.-H. Chen), bhsiao@mail.cjcu.edu.tw (B. Hsiao).

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existence of shared inputs among activities, or carry-over items between two consecutive terms. However, the structure of a bus transit firm is complex, with different activities and processes. In response to these operational characteristics of bus transit firms, a method that combines multiple activities, multiple processes and carry-over items, and that considers the allocation of shared resources, is designed to improve the weaknesses of the conventional DEA model. Early studies have tried to solve these weaknesses. In terms of the problem of “black box”, Beasley [3] and Mar Molinero [24] proposed a multi-activity DEA model to evaluate performance in each activity, simultaneously. Färe and Grosskopf [14,15] proposed a network DEA model for measuring performance with multiple processes. Afterward various models are proposed to measure the efficiencies of individual activities/processes. In terms of the problem of inter-temporal dependence, Färe and Grosskopf [14] also introduced a dynamic DEA model to study dynamical and historical systems. Nemoto and Goto [25] used the value-based model to examine dynamic structures. Emrouznejad and Thanassoulis [13] applied an input process distance measure to overcome the problem of inter-temporal input-output dependence. Tone and Tsutsui [30] proposed a dynamic slack-based DEA model to explore the effects of carry-over items. Kao and Liu [20] proposed a relational model to take the operations of individual periods into consideration. In addition, Yu and Lin [36], Yu and Fan [35], Chen [6], Chen et al. [7] and Wang et al. [34] provided multi-activity network DEA models which incorporated multiple activities and multiple processes into a unified framework. Bogetoft et al. [4] used a process distance measure model to study the dynamic network structure. Tone and Tsutsui [31] developed the dynamic network DEA model within the framework of slacks-based measures to deal with the effects of inter-connected processes and carry-over items. The dynamic network DEA models have been applied in the bank industry (e.g., [18,1,37]) and hospital industry (e.g., [21]).

With regard to studies in the bus transit industry, De Borger et al. [12] and De Borger and Kerstens [11] provided the comprehensive survey of the literature on the performance for bus transit operators. From their survey, we can find that most studies neglect the internal structure of bus transit firms and the effects of carry-over items. Although Chu et al. [8] considered the internal structure of bus transit firms and divided transit performance into efficiency and effectiveness, they applied separate models to evaluate these two performance indices, and ignored the inter-relationship between these two dimensions. Yu and Fan [35] combined these measures of PE, SEV and OEV into a single multi-activity network model to evaluate bus transit performance, but failed to take effects of carry-over items into consideration. However, the operation of a bus transit firm is not independent among periods. Some variables serve as carry-overs, persisting from one period to another. In consideration of long-term planning and investments, a single-period optimization model is not favorable. Hence, this paper proposes a novel method that combines the multi-activity, network and dynamic DEA models, called the multi-activity dynamic network DEA (MDNDEA) model, to assess performance. This model is designed to evaluate the performance achieved by firms which have several operational activities, processes and carry-over items between two consecutive terms. This framework provides the basis to explore the performance of individual activities, individual processes, individual periods, and overall operation in a unified model. In order to obtain more accurate measures and provide operators and policy makers more information on operational performance in the bus transit industry, the MDNDEA model is more appropriate.

The contributions of this paper are threefold. First, we propose an MDNDEA model, which accounts for the effects of inter-relationships among activities and processes as well as the impacts of carry-over items between two consecutive terms in a unified DEA framework. Second, undesirable outputs are included in this model to fully evaluate the performance of bus transit firms. Third, we use this model to assess the OEV of bus transit firms in Taiwan, and decompose OEV into the period-production efficiency of the HB service (PHBPE), period-production efficiency of the UB service (PUBPE) and period-service effectiveness (PSEV).

The rest of this paper is organized as follows. Section 2 proposes the methodology for evaluating various performance types in a unified model. Section 3 describes the data and discusses the empirical results and managerial implications. Finally, Section 4 presents the conclusions.

2. Methodology

The operation of a bus transit firm mainly includes two processes: production process and consumption process. The production process can be further divided into two activities: HB service and UB service. Parts of unseparated inputs are shared among activities and/or processes. For example, technicians need to maintain highway and urban buses, simultaneously; management staff members are responsible for the operation of the entire firm. In addition, the carry-over items exist in the bus transit industry, because the operation of a bus transit firm in one period is not independent of that in the next one. A bus transit firm usually continues activities over several periods. Those activities produced in the current period may cause an effect in the next period. For example, the network length generated in current period will drive the levels of production capacity in the next period. If these operational characteristics are ignored, performance measures may be misleading. Thus, the MDNDEA model, which considers the effects of inter-relationships among activities and processes as well as the impacts of carry-over items between two consecutive terms, is more suitable for this industry.

In the case of bus transit firms, outputs of transportation services may involve an undesirable output: the number of accidents. In order to deal with problems where some outputs (desirable outputs) are expected to be maximized and some outputs (undesirable outputs) are expected to be minimized, the directional distance function proposed by Luenberger [22] will be a more adequate tool. It permits simultaneous expansion of desirable outputs and contraction of undesirable outputs. Hence, we will build the performance measurement model by using the MDNDEA method and the directional distance function.

The operational framework is represented in Fig. 1. Specifically, some inputs are shared in HB and UB production activities (e.g., technicians), and some inputs are shared in HB production activity, UB production activity and consumption process (e.g., management staff). These production capacities of two activities are utilized as the inputs in the consumption process. In addition, some outputs in the production process in the current period will be transferred into the next period.

Suppose that there are J bus transit firms in period t ($t=1,\ldots,T$), and that each firm engages in HB and UB production activities as well as consumption process. Let $X^t_{aj,H}=(x^t_{1j,H},\ldots,x^t_{m_aj,H})$, $X^t_{bj,U}=(x^t_{1j,U},\ldots,\ x^t_{m_bj,U})$ and $X^t_{ej,C}=(x^t_{1j,C},\ldots,\ x^t_{m_ej,C})$ denote the dedicated input vectors associated with the HB production activity, UB production activity and consumption process in period t, respectively, and let $X^t_{cj,S}=(x^t_{1j,S},\ldots,\ x^t_{m_cj,S})$ and $X^t_{dj,SC}=(x^t_{1j,SC},\ldots,x^t_{m_dj,SC})$ be input vectors shared by HB production activity and UB production activity as well as by HB production activity, UB production activity and consumption process in period t, respectively. It is assumed that, in period t, firm j allocates some portion, $\mu^t_{cj,\ H}$, of the shared input quantities $x^t_{cj,S}$ to the HB production activity and the remaining $(1-\mu^t_{cj,\ H})$ to the UB production activity,