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

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Outline

- Introduction
- Methodology
- Empirical Results
- Conclusions

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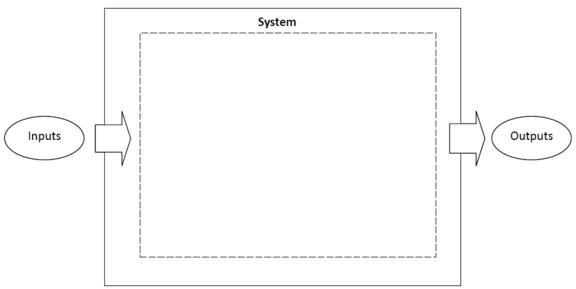
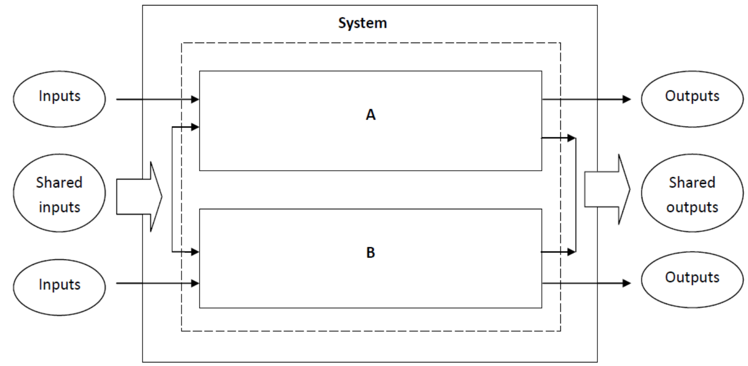
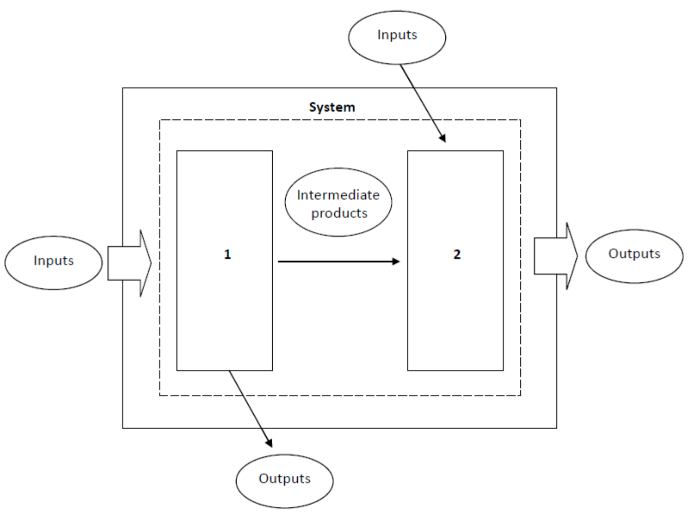
Introduction

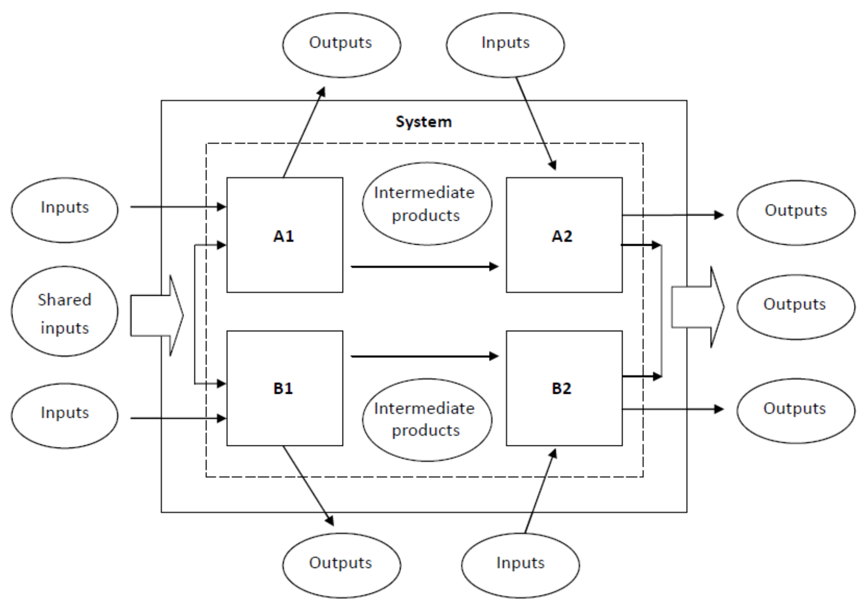
- In Taiwan, a bus transit firm primarily operates two activities and involves two processes.
  - Two activities: highway bus (HB) service and urban bus (UB) service
  - Two processes: production process and consumption process
- These services provided by bus transit firms are unstorable and must be consumed immediately.
- Conventional DEA models ignore the linking activities in parallel and in series, the existence of shared inputs as well as carry-over activities between two consecutive terms.

The evolution of DEA









The operational framework

- The operational framework

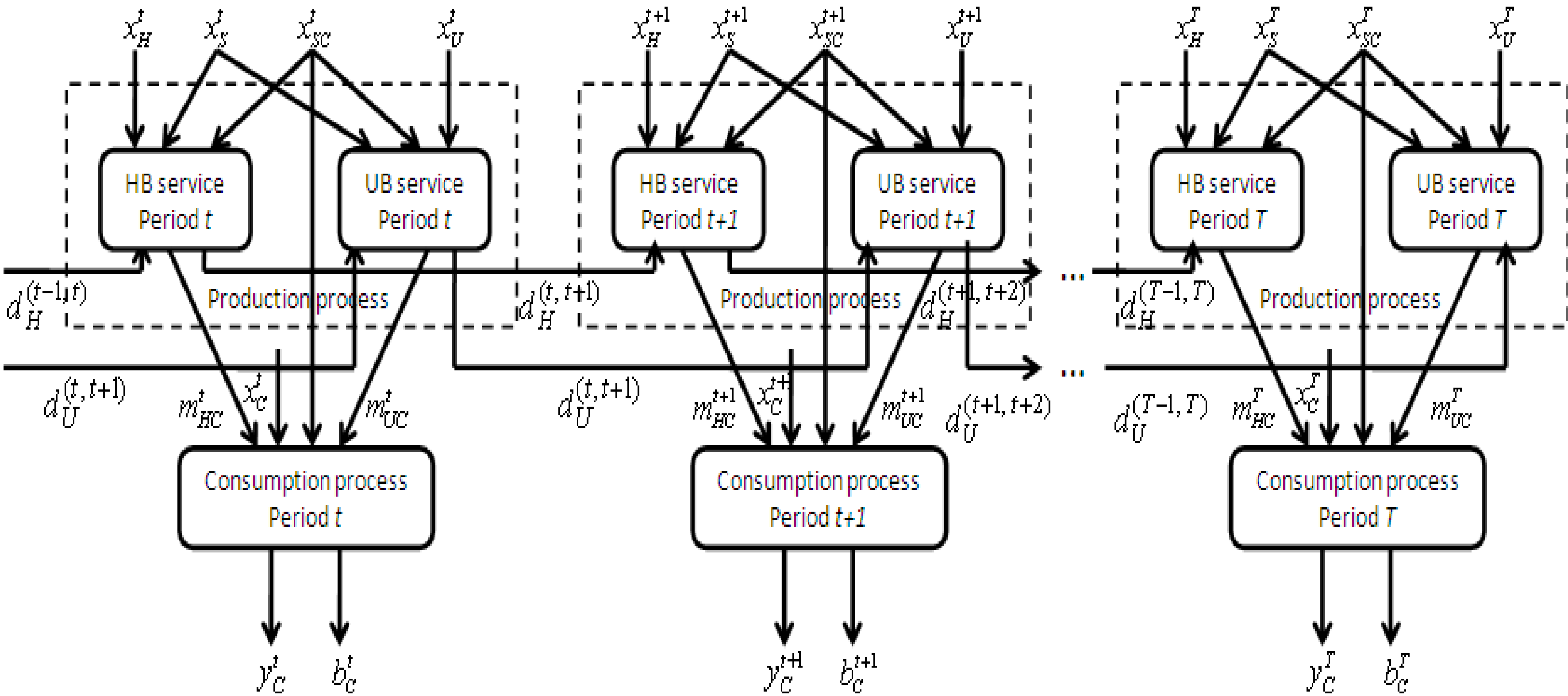


Fig. 1. The operational framework

Introduction

- Efficiency represents "do things right" and is measured by the production efficiency (PE).
  - The ratio of actual outputs produced to inputs.
- Effectiveness represents "do the right things" and is measured by the service effectiveness (SEV).
  - The ratio of consumed outputs to produced outputs.
- Operational effectiveness (OEV) is the combination of PE and SEV.
- These unique characteristics of bus transit services should be reflected and used to make the differentiation between the concepts of efficiency and effectiveness (Hatry, 1980).

Introduction

- The contributions of this paper:
  - We propose a multi-activity dynamic network DEA (MDNDEA) model, which accounts for the effects of inter-relationships among activities and processes as well as the impacts of carry-over activities between two consecutive terms in a unified DEA framework.
  - 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 activity (PHBPE), period-production efficiency of the UB activity (PUBPE) and period-service effectiveness (PSEV).

Outline

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Methodology

- Transportation services may involve the number of accidents (undesirable output).
- The directional distance function proposed by Luenberger (1992) permits simultaneous expansion of desirable outputs and contraction of undesirable outputs.
- We build the performance measurement model by using the MDNDEA method and the directional distance function.

Methodology

- The operational framework

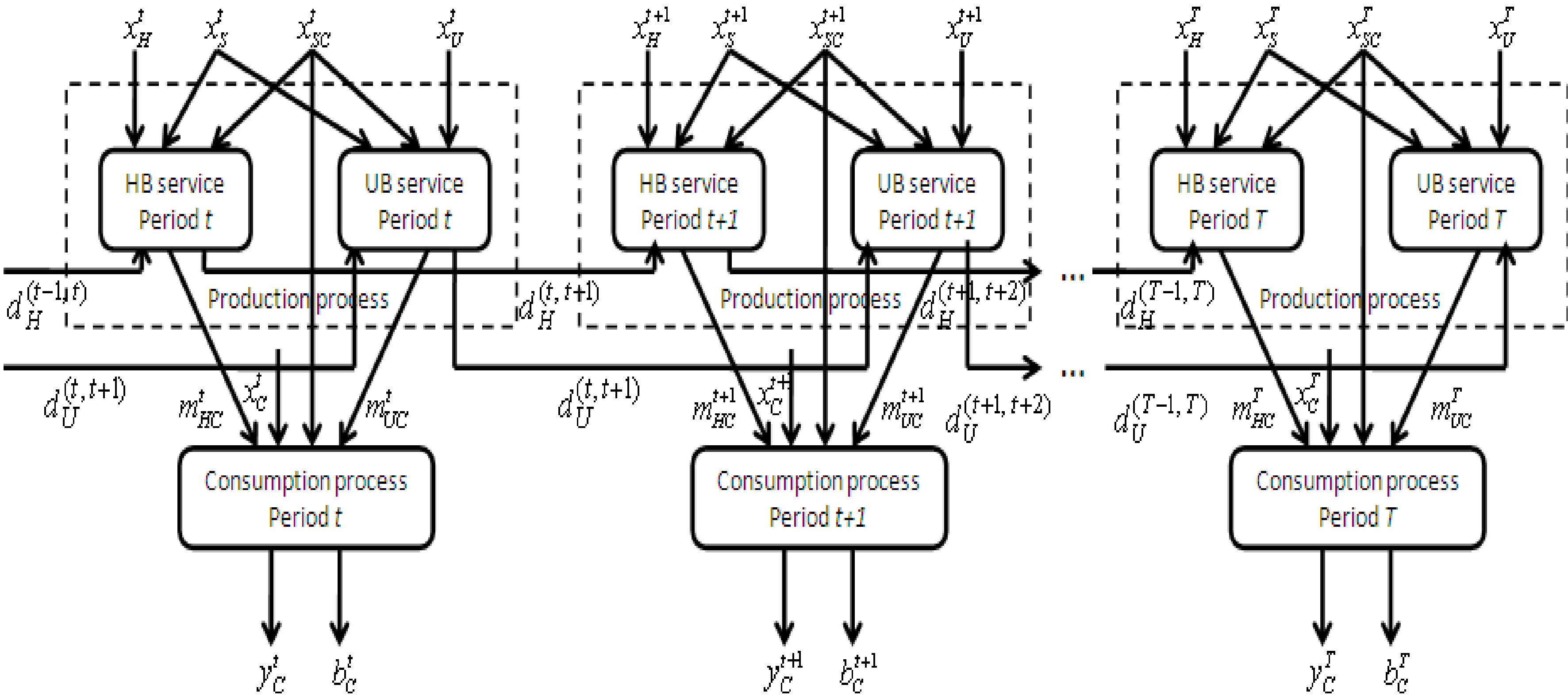

Fig. 1. The operational framework

Methodology

- The production technology of T_H^t for HB production activity under the assumption of constant returns to scale (CRS) is defined as follows:

$$
\begin{aligned}
T_H^t = \Big\{ (x^t, m^t, d^{(t,t+1)}) : & \sum_{j=1}^{J} \lambda_{j,H}^t x_{aj,H}^t \le x_{aj,H}^t, \quad a = 1,\ldots,m_a, \\
& \sum_{j=1}^{J} \mu_{cj,H}^t \lambda_{j,H}^t x_{cj,S}^t \le \mu_{cj,H}^t x_{cj,S}^t, \quad c = 1,\ldots,m_c, \\
& \sum_{j=1}^{J} \gamma_{dj,H}^t \lambda_{j,H}^t x_{dj,SC}^t \le \gamma_{dj,H}^t x_{dj,SC}^t, \quad d = 1,\ldots,m_d, \\
& 0 < \mu_{cj,H}^t < 1, \quad c = 1,\ldots,m_c,\ 0 < \gamma_{dj,H}^t < 1, \quad d = 1,\ldots,m_d, \\
& \sum_{j=1}^{J} \lambda_{j,H}^t m_{ij,HC}^t = m_{ij,HC}^t, \quad i = 1,\ldots,n_i, \\
& d_{pj,H}^{(t,t+1)} : free, \quad p = 1,\ldots,n_p,\ \lambda_{j,H}^t \ge 0, \quad j = 1,\ldots,J \Big\} \qquad (1)
\end{aligned}
$$

Methodology

- The production technology of T_U^t for UB production activity under the assumption of CRS is defined as follows:

$$T_U^t = \Big\{ (x^t, m^t, d^{(t,t+1)}) : \sum_{j=1}^{J} \lambda_{j,U}^t x_{bj,U}^t \le x_{bj,U}^t, \quad b = 1, \ldots, m_b,$$

$$\sum_{j=1}^{J} (1 - \mu_{cj,H}^t) \lambda_{j,U}^t x_{cj,S}^t \le (1 - \mu_{cj,H}^t) x_{cj,S}^t, \quad c = 1, \ldots, m_c,$$

$$\sum_{j=1}^{J} \gamma_{dj,U}^t \lambda_{j,U}^t x_{dj,SC}^t \le \gamma_{dj,U}^t x_{dj,SC}^t, \quad d = 1, \ldots, m_d,$$

$$0 < \mu_{cj,H}^t < 1, \quad c = 1, \ldots, m_c, \; 0 < \gamma_{dj,U}^t < 1, \quad d = 1, \ldots, m_d,$$

$$\sum_{j=1}^{J} \lambda_{j,U}^t m_{lj,UC}^t = m_{lj,UC}^t, \quad l = 1, \ldots, n_l,$$

$$d_{pj,U}^{(t,t+1)} : free, \quad q = 1, \ldots, n_q, \; \lambda_{j,U}^t \ge 0, \quad j = 1, \ldots, J \Big\} \qquad (2)$$

Methodology

- The production technology of T_C^t for consumption service under the assumption of CRS is defined as follows:

$$T_C^t = \Big\{ (x^t, m^t, y^t) : \sum_{j=1}^{J} \lambda_{j,C}^t x_{ej,C}^t \le x_{ej,C}^t, \quad e = 1, \dots, m_e,$$

$$\sum_{j=1}^{J} (1 - \gamma_{dj,H}^t - \gamma_{dj,U}^t) \lambda_{j,C}^t x_{dj,SC}^t \le (1 - \gamma_{dj,H}^t - \gamma_{dj,U}^t) x_{dj,SC}^t, \quad d = 1, \dots, m_d,$$

$$0 < \gamma_{dj,H}^t < 1, \quad d = 1, \dots, m_d, \ 0 < \gamma_{dj,C}^t < 1, \quad d = 1, \dots, m_d,$$

$$\sum_{j=1}^{J} \lambda_{j,C}^t m_{ij,HC}^t = m_{ij,HC}^t, \quad i = 1, \dots, n_i,$$

$$\sum_{j=1}^{J} \lambda_{j,C}^t m_{lj,UC}^t = m_{lj,UC}^t, \quad l = 1, \dots, n_l,$$

$$\sum_{j=1}^{J} \lambda_{j,C}^t y_{fj,C}^t \ge y_{fj,C}^t, \quad f = 1, \dots, s_f,$$

$$\sum_{j=1}^{J} \lambda_{j,C}^t b_{gj,C}^t = b_{gj,C}^t, \quad g = 1, \dots, s_g, \ \lambda_{j,C}^t \ge 0, \quad j = 1, \dots, J \Big\} \qquad (3)$$

Methodology

- The operational ineffectiveness for bus transit firm *k* can be estimated by solving the following MDNDEA model based on a directional distance function:

Objection function:

$$\vec{D}(x_k, m_k, d_k, y_k) = \max \beta_k = \sum_{t=1}^{T} W^t \left[w^P (w^H \cdot \beta_{k,H}^t + w^U \cdot \beta_{k,U}^t) + w^C \cdot \beta_{k,C}^t \right] \quad (4)$$

Methodology

Subject to

a. HB production activity:

$$\sum_{j=1}^{J} \lambda_{j,H}^{t} x_{aj,H}^{t} \leq (1-\beta_{k,H}^{t}) x_{ak,H}^{t}, \quad a=1,\ldots,m_a, t=1,\ldots,T \tag{4.1}$$

$$\sum_{j=1}^{J} \lambda_{j,H}^{t} m_{ij,HC}^{t} = m_{ik,HC}^{t}, \quad i=1,\ldots,n_i, t=1,\ldots,T \tag{4.2}$$

$$\sum_{j=1}^{J} \lambda_{j,H}^{t} d_{pj,H}^{(t,t+1)} = \sum_{j=1}^{J} \lambda_{j,H}^{t+1} d_{pj,H}^{(t,t+1)}, \quad p=1,\ldots,n_p, t=1,\ldots,T-1 \tag{4.3}$$

$$\sum_{j=1}^{J} \lambda_{j,H}^{t} d_{pj,H}^{(t,t+1)} = d_{pk,H}^{(t,t+1)} - S_{pk,H}^{(t,t+1),\ free}, \quad p=1,\ldots,n_p, t=1,\ldots,T-1 \tag{4.4}$$

$$S_{pk,H}^{(t,t+1),\ free} = S_{pk,H}^{(t,t+1),\ free-} - S_{pk,H}^{(t,t+1),\ free+}, \quad S_{pk,H}^{(t,t+1),\ free-} \geq 0, S_{pk,H}^{(t,t+1),\ free+} \geq 0 \tag{4.5}$$

$$S_{pk,H}^{(t,t+1),\ free-} \leq M \delta_{pk,H}^{t}, S_{pk,H}^{(t,t+1),\ free+} \leq M (1-\delta_{pk,H}^{t}) \tag{4.6}$$

Methodology

b. UB production activity:

$$\sum_{j=1}^{J} \lambda_{j,U}^{t} x_{bj,U}^{t} \leq (1-\beta_{k,U}^{t}) x_{bk,U}^{t}, \quad b=1,\ldots,m_b,\ t=1,\ldots,T \tag{4.7}$$

$$\sum_{j=1}^{J} \lambda_{j,U}^{t} m_{lj,UC}^{t} = m_{lk,UC}^{t}, \quad l=1,\ldots,n_l,\ t=1,\ldots,T \tag{4.8}$$

$$\sum_{j=1}^{J} \lambda_{j,U}^{t} d_{qj,U}^{(t,t+1)} = \sum_{j=1}^{J} \lambda_{j,U}^{t+1} d_{qj,U}^{(t,t+1)}, \quad q=1,\ldots,n_q,\ t=1,\ldots,T-1 \tag{4.9}$$

$$\sum_{j=1}^{J} \lambda_{j,U}^{t} d_{qj,U}^{(t,t+1)} = d_{qk,U}^{(t,t+1)} - S_{qk,U}^{(t,t+1),\ free}, \quad q=1,\ldots,n_q,\ t=1,\ldots,T-1 \tag{4.10}$$

$$S_{qk,U}^{(t,t+1),\ free} = S_{qk,U}^{(t,t+1),\ free-} - S_{qk,U}^{(t,t+1),\ free+}, \quad S_{qk,U}^{(t,t+1),\ free-} \geq 0,\ S_{qk,U}^{(t,t+1),\ free+} \geq 0 \tag{4.11}$$

$$S_{qk,U}^{(t,t+1),\ free-} \leq M\delta_{qk,H}^{t},\ S_{qk,U}^{(t,t+1),\ free+} \leq M(1-\delta_{qk,U}^{t}) \tag{4.12}$$

Methodology

c. Consumption process:

$$\sum_{j=1}^{J} \lambda_{j,C}^{t} x_{ej,C}^{t} \leq (1-\beta_{k,C}^{t}) x_{ek,C}^{t}, \quad e=1,\ldots,m_e, t=1,\ldots,T \tag{4.13}$$

$$\sum_{j=1}^{J} \lambda_{j,C}^{t} m_{ij,HC}^{t} = m_{ik,HC}^{t}, \quad i=1,\ldots,n_i, t=1,\ldots,T \tag{4.14}$$

$$\sum_{j=1}^{J} \lambda_{j,C}^{t} m_{lj,UC}^{t} = m_{lk,UC}^{t}, \quad l=1,\ldots,n_l, t=1,\ldots,T \tag{4.15}$$

$$\sum_{j=1}^{J} \lambda_{j,C}^{t} y_{fj,C}^{t} \geq (1+\beta_{k,C}^{t}) y_{fk,C}^{t}, \quad f=1,\ldots,s_f, t=1,\ldots,T \tag{4.16}$$

$$\sum_{j=1}^{J} \lambda_{j,C}^{t} b_{gj,C}^{t} = (1-\beta_{k,C}^{t}) b_{gk,C}^{t}, \quad g=1,\ldots,s_g, t=1,\ldots,T \tag{4.17}$$

Methodology

d. Shared inputs:

$$\sum_{j=1}^{J} \mu^t_{cj,H} \lambda^t_{j,H} x^t_{cj,S} \le (1-\beta^t_{k,H}) \mu^t_{ck,H} x^t_{ck,S}, \quad c=1,\ldots,m_c, t=1,\ldots,T \quad (4.18)$$

$$\sum_{j=1}^{J} (1-\mu^t_{cj,H}) \lambda^t_{j,U} x^t_{cj,S} \le (1-\beta^t_{k,U})(1-\mu^t_{ck,H}) x^t_{ck,S}, \quad c=1,\ldots,m_c, t=1,\ldots,T \quad (4.19)$$

$$\sum_{j=1}^{J} \gamma^t_{dj,H} \lambda^t_{j,H} x^t_{dj,SC} \le (1-\beta^t_{k,H}) \gamma^t_{dk,H} x^t_{dk,SC}, \quad d=1,\ldots,m_d, t=1,\ldots,T \quad (4.20)$$

$$\sum_{j=1}^{J} \gamma^t_{dj,U} \lambda^t_{j,U} x^t_{dj,SC} \le (1-\beta^t_{k,U}) \gamma^t_{dk,U} x^t_{dk,SC}, \quad d=1,\ldots,m_d, t=1,\ldots,T \quad (4.21)$$

$$\sum_{j=1}^{J} (1-\gamma^t_{dj,H}-\gamma^t_{dj,U}) \lambda^t_{j,C} x^t_{dj,SC} \le (1-\beta^t_{k,U})(1-\gamma^t_{dk,H}-\gamma^t_{dk,U}) x^t_{dk,SC}, \quad d=1,\ldots,m_d, t=1,\ldots,T \quad (4.22)$$

$$L^t_{c,H} < \mu^t_{c,H} < U^t_{c,H}, \quad c=1,\ldots,m_c, t=1,\ldots,T \quad (4.23)$$

$$L^t_{d,H} < \gamma^t_{d,H} < U^t_{d,H}, \quad d=1,\ldots,m_d, t=1,\ldots,T \quad (4.24)$$

$$L^t_{d,U} < \gamma^t_{d,U} < U^t_{d,U}, \quad d=1,\ldots,m_d, t=1,\ldots,T \quad (4.25)$$

Methodology

e. Initial conditions:

$$\sum_{j=1}^{J} \lambda_{j,H}^{1} d_{pj,H}^{(0,1)} = d_{pk,H}^{(0,1)}, \quad p = 1,\ldots,n_p,$$

$$\sum_{j=1}^{J} \lambda_{j,U}^{1} d_{qj,U}^{(0,1)} = d_{qk,U}^{(0,1)}, \quad q = 1,\ldots,n_q,$$

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

$$w^{H} + w^{U} = 1$$

$$w^{P} + w^{C} = 1$$

$$\lambda_{j,H}, \lambda_{j,U}, \lambda_{j,C}, W^{t}, w^{H}, w^{U}, w^{P}, w^{C} \geq 0, \quad j = 1,\ldots,J, t = 1,\ldots,T$$

(4.26)

Methodology

- Three basic measures
  - PHBPE: $1-\beta_{k,H}^{t}$
  - PUBPE: $1-\beta_{k,U}^{t}$
  - PSEV: $1-\beta_{k,C}^{t}$

Methodology

- Seven induced measures
  - Period-production efficiency (PPE): $1-(w^H \cdot \beta^t_{k,H} + w^U \cdot \beta^t_{k,U})$
  - Period-operational effectiveness (POEV): $1-[w^P(w^H \cdot \beta^t_{k,H} + w^U \cdot \beta^t_{k,U}) + w^C \cdot \beta^t_{k,C}]$
  - Production efficiency of the HB activity (HBPE): $1-\sum_{t=1}^{T} W^t \cdot \beta^t_{k,H}$
  - Production efficiency of the UB activity (UBPE): $1-\sum_{t=1}^{T} W^t \cdot \beta^t_{k,U}$
  - PE: $1-\sum_{t=1}^{T} W^t (w^H \cdot \beta^t_{k,H} + w^U \cdot \beta^t_{k,U})$
  - SEV: $1-\sum_{t=1}^{T} W^t \cdot \beta^t_{k,C}$
  - OEV: $1-\beta_k$

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  - Managerial implications
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The data

- Data: 20 bus transit firms in Taiwan for the period 2004-2012
- Dedicated Inputs for HB and UB services:
  - The number of drivers
  - The total number of vehicles operated at maximum service
  - The number of liters of fuel
- Dedicated Input for consumption service:
  - The number of ticket agents
- Shared input between HB and UB services:
  - The number of technicians

The data

- Shared input among HB, UB and consumption services:
  - The number of management staffs
- Intermediate output for HB and UB services:
  - vehicle-kms
- Outputs for consumption service:
  - Desirable outputs: HB Passenger-kms and UB Passenger-kms
  - Undesirable output: The number of accidents
- Carry-over activity:
  - Network length of HB and UB services

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Table 2. Operational effectiveness and its components of individual bus transit firms

Firm	OEV	PE	HBPE	UBPE	SEV
Sanchung	0.8729 (9)	0.7459 (14)	0.4917 (19)	1.0000 (1)	1.0000 (1)
Capital	0.8816 (8)	0.7633 (13)	0.5770 (17)	0.9496 (8)	1.0000 (1)
Taipei	0.8469 (12)	0.6937 (17)	0.3874 (20)	1.0000 (1)	1.0000 (1)
Chih-nan	0.8919 (5)	0.7837 (10)	0.5875 (16)	0.9799 (7)	1.0000 (1)
CitiAir	0.8180 (15)	0.9715 (3)	1.0000 (1)	0.9431 (10)	0.6644 (19)
Chung-shing	0.7566 (18)	0.6880 (18)	0.8069 (12)	0.5692 (17)	0.8252 (16)
Kuang-hua	0.7930 (16)	0.9229 (5)	0.8458 (9)	1.0000 (1)	0.6631 (20)
Tansui	0.9347 (4)	0.9358 (4)	0.8717 (8)	1.0000 (1)	0.9336 (13)
Chungli	0.9444 (2)	0.8966 (6)	0.7932 (13)	1.0000 (1)	0.9923 (10)
Taoyuan	0.7776 (17)	0.5553 (20)	0.4997 (18)	0.6108 (15)	1.0000 (1)
Hsinchu	0.8519 (11)	0.7038 (16)	0.9372 (6)	0.4704 (19)	1.0000 (1)
Hualien	0.9871 (1)	0.9743 (2)	1.0000 (1)	0.9485 (9)	1.0000 (1)
Fengyuan	0.8217 (14)	0.7650 (12)	1.0000 (1)	0.5300 (18)	0.8783 (15)
Taichung	0.8846 (6)	0.7961 (9)	0.7897 (14)	0.8025 (12)	0.9731 (11)
Changhua	0.8818 (7)	0.7679 (11)	0.9628 (5)	0.5729 (16)	0.9958 (9)
Ubus	0.8618 (10)	0.7236 (15)	0.8306 (10)	0.6166 (14)	1.0000 (1)
Geya	0.7507 (20)	0.5564 (19)	0.8114 (11)	0.3013 (20)	0.9451 (12)
Kaohsiung	0.7511 (19)	0.8145 (8)	0.6884 (15)	0.9406 (11)	0.6877 (18)
Pingtung	0.8284 (13)	0.8609 (7)	0.9269 (7)	0.7949 (13)	0.7959 (17)
Chiayi	0.9440 (3)	1.0000 (1)	1.0000 (1)	1.0000 (1)	0.8880 (14)
Average	0.8540	0.7960	0.7904	0.8015	0.9121
Std. Dev.	0.0681	0.1280	0.1907	0.2250	0.1207
Max	0.9871	1.0000	1.0000	1.0000	1.0000
Min	0.7507	0.5553	0.3874	0.3013	0.6631

Note: Rankings are provided in parentheses.

Performance results

- The average POEV scores maintain the stable variance over the sample period.
- The average PSEV scores reveal the higher levels over the sample period.
  - This implies that transit bus firms perform well in the consumption process over the sample period.

Table 3. Period-operational effectiveness and its components, 2004-2012

Year	POEV	PPE	PHBPE	PUBPE	PSEV
2004	0.8626	0.7613	0.7744	0.7482	0.9638
2005	0.8874	0.8125	0.8627	0.7623	0.9623
2006	0.8401	0.7770	0.7992	0.7548	0.9033
2007	0.8095	0.7651	0.8279	0.7023	0.8540
2008	0.8852	0.8503	0.7963	0.9044	0.9200
2009	0.8691	0.7923	0.7640	0.8206	0.9459
2010	0.8378	0.7442	0.6905	0.7979	0.9314
2011	0.8210	0.7846	0.7708	0.7985	0.8593
2012	0.8726	0.8762	0.8280	0.9245	0.8690
2004-2012	0.8540	0.7960	0.7904	0.8015	0.9121

Performance results

- PHBPE and PUBPE appear to similar patterns over the sample period.

Table 3. Period-operational effectiveness and its components, 2004-2012

Year	POEV	PPE	PHBPE	PUBPE	PSEV
2004	0.8626	0.7613	0.7744	0.7482	0.9638
2005	0.8874	0.8125	0.8627	0.7623	0.9623
2006	0.8401	0.7770	0.7992	0.7548	0.9033
2007	0.8095	0.7651	0.8279	0.7023	0.8540
2008	0.8852	0.8503	0.7963	0.9044	0.9200
2009	0.8691	0.7923	0.7640	0.8206	0.9459
2010	0.8378	0.7442	0.6905	0.7979	0.9314
2011	0.8210	0.7846	0.7708	0.7985	0.8593
2012	0.8726	0.8762	0.8280	0.9245	0.8690
2004-2012	0.8540	0.7960	0.7904	0.8015	0.9121

Performance results

- The correlation coefficients are significantly positive between OEV and PE as well as OEV and SEV.
  - Both production and consumption sides are important in terms of the variances in OEV of bus transit firms.
- The correlation coefficient is not significant between PE and SEV.
  - A higher PE does not guarantee a lower SEV.

Table 4. Correlation coefficients between operational effectiveness and its components

	OEV	PE	SEV
OEV	1.0000		
PE	0.5839*	1.0000	
SEV	0.5095*	-0.4010	1.0000

Note: * is significant at the 5% level.

Performance results

- The correlation coefficients are significantly positive between PE and HBPE as well as PE and UBPE.
  - The PE is achieved by both HBPE and UBPE.
- The correlation coefficient is insignificantly negative between HBPE and UBPE.
  - The enhancement of efficiency in the HB activity does not necessarily decrease the efficiency in the UB activity.

Table 5. Correlation coefficients between production efficiency and its components

	PE	HBPE	UBPE
PE	1.0000		
HBPE	0.5253*	1.0000	
UBPE	0.6926*	-0.2499	1.0000

Note: * is significant at the 5% level.

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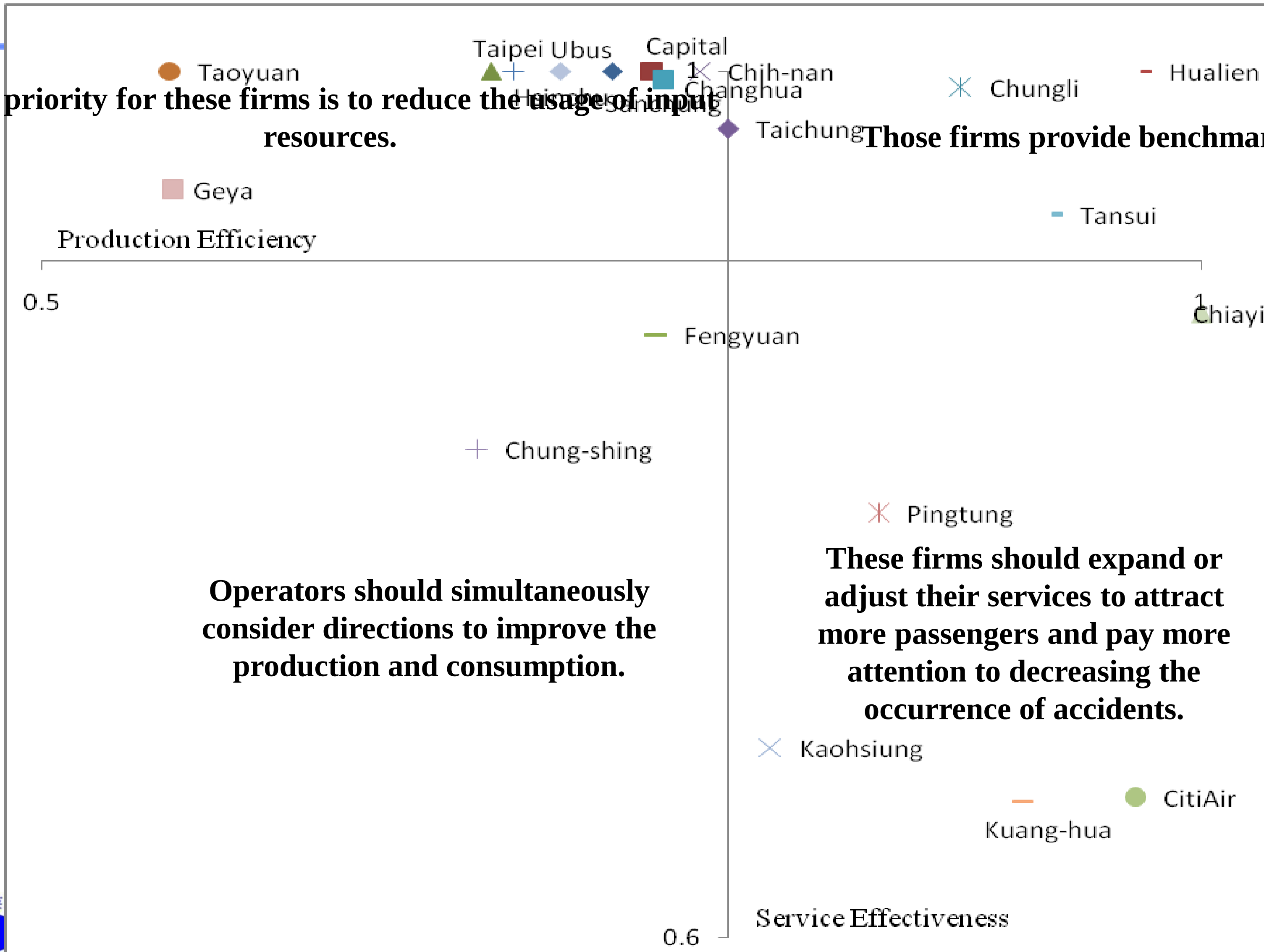
The priority for these firms is to reduce the usage of input resources.

Those firms provide benchmarks for others.



These firms should expand or adjust their services to attract more passengers and pay more attention to decreasing the occurrence of accidents.

Operators should simultaneously consider directions to improve the production and consumption.

Managerial implications

- First, six bus transit firms have higher HBPE and UBPE.
  - CitiAir, Kuang-hua, Tansui, Chungli, Hualien and Chiayi.
  - Those best-performing firms should maintain their HBPE and UBPE.
- Second, six bus transit firms have lower HBPE and higher UBPE.
  - Sanchung, Capital, Taipei, Chih-nan, Taichung and Kaohsiung
  - Those bus transit firms should focus on their HB service and improve the input resources utilization in this activity.

Managerial implications

- Tayuan experiences lower HBPE and UBPE.
  - It should adjust the usage of inputs in HB and UB activities, simultaneously.
- Fourth, seven bus transit firms have higher HBPE, but lower UBPE.
  - Chung-shing, Hsinchu, Fengyuan, Changhua, Ubus, Geya and Pingtung.
  - The priority for these firms is to improve the UBPE by controlling the usage of input resources in the UB activity.

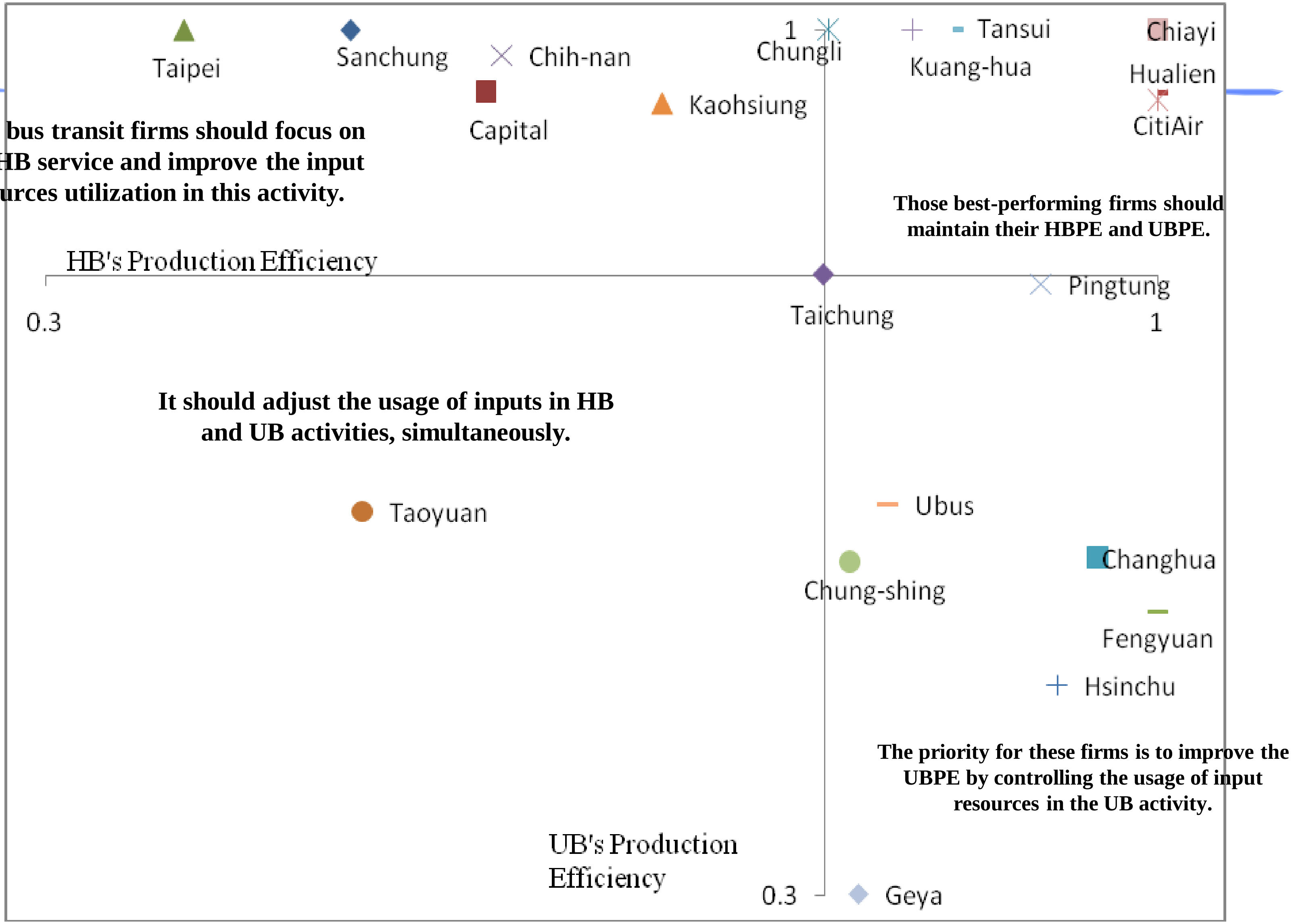


Fig. 3. HB’s production efficiency vs. UB’s production efficiency

Outline

- Introduction
- Methodology
- Empirical results
- Conclusions

Conclusions

- The average POEV scores maintain the stable variance.
- Highway and urban bus services appear to similar patterns of period efficiency.
- Transit bus firms perform well in the consumption process.
- The sources of operational ineffectiveness among bus transit firms are different.

Conclusions

- The main advantage of the proposed MDNDEA model is that the linkage between activities /processes, these shared inputs among activities /processes, and the effects of carry-over activities are included in this unified model so as to provide more appropriate measures of performance.

Thank you for your attention!