MEASURING LOGISTICS EFFICIENCY AT KEY BORDER PORTS IN CHINA: A GENERALIZED DEA APPROACH BASED ON PANEL DATA

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Abstract

The study measured the logistics efficiency of China's principal land border ports and explained the differences observed among them. The author defined border port efficiency as the ratio of the gain in port competitiveness to effective construction investment within one year, and built an index system with fixed asset investment per unit area as the input and cargo volume, passenger flow and vehicle flow as the outputs. A generalized data envelopment analysis model for panel data was applied, with 2017 taken as the base year for the production possibility set. Ten first-class highway ports were evaluated for 2018-2021 and grouped into three efficiency classes. The results showed that investment returns depended on the developmental stage of each port rather than on investment volume alone.

Keywords: border ports; logistics efficiency; generalized DEA; panel data; port competitiveness; fixed asset investment; cross-border trade.

Annotatsiya

Tadqiqotda Xitoyning asosiy quruqlik chegara portlari logistika samaradorligi o‘lchandi va ular o‘rtasidagi farqlarning sabablari izohlandi. Muallif chegara porti samaradorligini bir yil ichidagi port raqobatbardoshligi o‘sishining qurilishga qilingan samarali investitsiyalarga nisbati sifatida ta’rifladi hamda kirish ko‘rsatkichi sifatida maydon birligiga to‘g‘ri keladigan asosiy vositalar investitsiyasini, chiqish ko‘rsatkichlari sifatida yuk hajmi, yo‘lovchi va transport vositalari oqimini oldi. Panel ma’lumotlar uchun umumlashtirilgan ma’lumotlar qobig‘i tahlili modeli qo‘llanildi, ishlab chiqarish imkoniyatlari to‘plami uchun 2017-yil bazis sifatida tanlandi. O‘nta birinchi toifali avtomobil porti 2018-2021-yillar bo‘yicha baholanib, uch samaradorlik guruhiga ajratildi. Natijalar investitsiya qaytimi port rivojlanish bosqichiga bog‘liqligini ko‘rsatdi.

Kalit so‘zlar: chegara portlari; logistika samaradorligi; umumlashtirilgan DEA; panel ma’lumotlar; port raqobatbardoshligi; asosiy vositalar investitsiyasi; transchegaraviy savdo.

Аннотация

В исследовании измерена логистическая эффективность основных наземных пограничных портов Китая и объяснены различия между ними. Автор определил эффективность пограничного порта как отношение прироста его конкурентоспособности к эффективным инвестициям в строительство в течение года и построил систему показателей, в которой входным параметром выступили инвестиции в основные фонды на единицу площади, а выходными - объём грузов, поток пассажиров и поток транспортных средств. Была применена обобщённая модель анализа среды функционирования для панельных данных,

где базой множества производственных возможностей стал 2017 год. Десять пограничных автомобильных портов первой категории оценены за 2018-2021 годы и разделены на три группы. Результаты показали зависимость отдачи инвестиций от этапа развития порта.

Ключевые слова: пограничные порты; логистическая эффективность; обобщённая DEA; панельные данные; конкурентоспособность порта; инвестиции в основные фонды; трансграничная торговля.

INTRODUCTION

Since the late 1980s China has opened its land border ports on a large scale, and their development has become increasingly intertwined with that of the coastal ports, ending the long-standing isolation of the frontier regions. As an opening-up pattern combining simultaneous development in the east and the west with complementarity between the north and the south took shape, border ports emerged as vital platforms for trade connectivity. Early research on the spatial layout of the country's open ports already noted that their placement follows geographical position and radiation function, and that the political and economic conditions of neighbouring states largely determine the trade partners available to each crossing [1]. Since 2013 the Belt and Road Initiative has further strengthened the operational capacity and trade performance of these ports.

Ports are locations designated by the state to manage foreign economic and trade activities and international exchanges. They include seaports, railway stations and border crossings through which people, goods and means of transport enter and leave the national territory, and in this sense they constitute special nodes of the international logistics network. Modern ports have moved far beyond their original function as channels for foreign trade and have become comprehensive gateways for scientific and technological exchange, cultural dissemination and the movement of travellers.

Land border ports, also called border crossings, form a specific category. The concept rests on the interpretation of the term border, which in the Chinese context denotes the land frontiers of the country - socio-economic regions with legally defined national boundaries that directly adjoin foreign territory and extend inland to include a hinterland along the inner side of the boundary. Because of this geographical particularity, the planning and construction of a land border port require bilateral negotiation and a joint assessment between neighbouring governments before the crossing can be opened at a specific location within the sovereign territory of the host state. Studies of the national border port system have emphasised that these crossings are widely dispersed and differ substantially in operational performance [2], which makes comparative measurement a meaningful research task.

The measurement of border port efficiency turns on the balance between inputs and outputs - that is, on whether a given level of investment in port construction yields the maximum attainable output. On the input side, the utilisation of port resources is reflected primarily in the construction and operation of infrastructure. On the output side, the most immediate consequence of higher throughput is the strengthening of port competitiveness. Accordingly, this paper defines the efficiency of a land border port as

the ratio of the improvement in port competitiveness to effective construction inputs within a given period, normally one year. Such a definition places border ports within the broader discussion of how the country's port system interacts under the dual circulation pattern [3], while retaining the specific features of land crossings.

LITERATURE REVIEW

Research on border port logistics has developed along three lines: studies of the operating environment and functional roles of individual crossings, geographical analyses of the spatial pattern of the port system, and assessments of port competitiveness and its links with the hinterland economy.

Within the first line, analyses of the logistics environment of border ports in Northeast China examined the factors acting at the macro, meso and micro levels and identified both the favourable conditions and the principal constraints facing regional port development at that stage [4]. Work devoted specifically to the China-Russia corridor extended this analysis to the organisation of cross-border logistics along the whole route [5], while a parallel study of the state and prospects of Sino-Russian cross-border logistics trade proposed functional roles for border logistics as a system and for individual port nodes within it [6].

The second line adopts a geographical perspective. A study of the spatiotemporal pattern of border port development characterised the distribution of crossings across the frontier and, using a relative concentration index, produced a quantitative typology of port-city relationships and their evolution [7]. Regional monographs complemented this picture by describing the logistics system of the ports of a single frontier province in detail [8]. Later research examined the coordinated development of a border railway port and the economy of its hinterland, showing that the two evolve jointly rather than independently [9].

The third line addresses competitiveness. An assessment of the comprehensive competitiveness of thirteen border ports of a single autonomous region under the dual circulation perspective demonstrated that the ranking of crossings depends on the indicator set adopted [10]. Studies of the governance capacity of border port cities, including their handling of public health emergencies, show that the administrative environment surrounding a crossing also conditions its performance [11]. The political economy of port opening provides the analytical basis for treating competitiveness as the central output of a border crossing and for selecting the indicators that represent it [12].

Two observations follow from this review. First, the efficiency and development models of coastal ports are comparatively well studied, whereas border ports have received far less attention; the coastal model was for a time regarded as a template for frontier crossings to emulate, yet differences in historical background, trade partners and functional positioning mean that border port development cannot simply replicate it and must be examined against the industrial conditions of the border cities themselves. Second, scholars have paid limited attention to the relationship between infrastructure investment and the resulting competitiveness of specific crossings.

Comparing the efficiency of the major border ports and identifying the sources of the differences between them is therefore of practical significance.

METHODOLOGY

Data envelopment analysis in its traditional form uses data on a set of decision-making units observed within a single time period, that is, cross-sectional data. When the evaluation covers panel data spanning several periods, the external environment of the units changes over time, so applying the traditional model would conflict with its own assumptions. In economic terms, evaluating panel data with the traditional model implies that production technology remains constant at every point in time and therefore disregards technological progress, which is inconsistent with observed conditions. This paper accordingly applies the generalized DEA method, which constructs the production possibility set from a chosen base period and evaluates the units of later periods against it [13].

Let m input indicators and s output indicators be used to examine the input-output performance of n homogeneous decision-making units observed over L time periods. For the j-th unit in the k-th period the input vector is $x_j^{(k)} = (x_{1j}^{(k)}, x_{2j}^{(k)}, \ldots, x_{mj}^{(k)})^T$ and the output vector is $y_j^{(k)} = (y_{1j}^{(k)}, y_{2j}^{(k)}, \ldots, y_{sj}^{(k)})^T$, where $x_j^{(k)} > 0$ and $y_j^{(k)} > 0$ for $j = 1, 2, \ldots, n$ and $k = 1, 2, \ldots, L$. The corresponding base-period vectors are $x_j^{(0)}$ and $y_j^{(0)}$, and all indicator values are assumed positive.

Using the base-period observations as the sample, the production possibility set of the base year is constructed as

$$T = \{ (x, y) \mid x \geq \Sigma_j x_j^{(0)} \lambda_j , \quad y \leq \Sigma_j y_j^{(0)} \lambda_j , \quad \delta \Sigma_j \lambda_j = \delta , \quad (\lambda_1, \ldots, \lambda_n) \geq 0 \}, \quad j = 1, \ldots, n^{(0)}$$

where λ_j are the intensity weights and δ takes the value one when the model is specified with variable returns to scale and zero otherwise. The efficiency of each unit is then assessed relative to this set. For the indicator values $(x_j^{(k)}, y_j^{(k)})$ of the j-th unit in the k-th period, if no point (x, y) belonging to T satisfies $x_j^{(k)} \geq x$ and $y_j^{(k)} \leq y$ with at least one strict inequality, the unit is said to be D-panel efficient in that period. The degree of effectiveness is measured through the following programme:

$$\min \theta - \varepsilon (\hat{e}^t s^- + e^t s^+)$$

$$\text{s.t.} \quad \Sigma_j \lambda_j x_j^{(0)} + s^- = \theta x_p^{(k)} ; \quad \Sigma_j \lambda_j y_j^{(0)} - s^+ = y_p^{(k)} ; \quad \delta \Sigma_j \lambda_j = \delta ; \quad \lambda_j \geq 0 ; \quad s^+ \geq 0 ; \quad s^- \geq 0$$

where θ is the efficiency score of the evaluated unit p, s^- and s^+ are the input and output slack variables and ε is a non-Archimedean infinitesimal. If the programme has no feasible solution, or if its optimal value satisfies $\theta^0 \geq 1$, the production of the unit in the period concerned is termed D-panel weakly efficient. The solution is interpreted through four cases. When $\theta^0 > 1$, the productive efficiency of unit p in period k exceeds that of the base year, and the larger θ^0 is, the greater the improvement over the reference set. When $\theta^0 = 1$ and the slack vector (s^{+0}, s^{-0}) equals zero, efficiency is equivalent to that of the base year. When $\theta^0 = 1$ and the slack vector differs from zero, the unit is weakly efficient relative to the base year, since a residual input surplus or output shortfall remains. When $\theta^0 < 1$, efficiency is inferior to that of the base year.

In this study 2017 is taken as the base year for constructing the production possibility set, and the efficiency of the sample ports is evaluated for the period 2018-2021 on the basis of panel data.

ANALYSIS AND RESULTS

Selecting representative efficiency indicators for border ports requires several principles to be observed: data availability, uniformity of statistical standards, comprehensiveness and parsimony. Because the volume of existing research on port efficiency is limited, no established indicator system was available for direct reference. Treating ports as specialised transfer nodes of the international logistics network and taking account of the functional similarities among them, this paper synthesises the indicator systems adopted in earlier DEA studies of logistics and port performance, summarised in Table 1, and on that basis proposes a system suited to border crossings.

Table 1.

Input and output indicators used in earlier DEA studies of logistics and port efficiency[1]

Sources	Input indicators	Output indicators
[14]	Fixed asset investment in transport, storage and postal services; number of employees	Freight turnover; passenger turnover
[15]	Classified road mileage; civil vehicle ownership; employees in transport, warehousing, postal and communication industries	Highway freight volume; city GDP
[16]	Comprehensive capacity; number of operational berths; infrastructure construction investment	Cargo throughput; container throughput; port freight volume and turnover
[17]	Number of berths; dock shoreline length; area and storage capacity of yards; annual growth of fixed assets	Port cargo throughput; container throughput; port operating income
[18]	Port clearance time	Ratio of import declaration forms

On the input side, fixed assets form the foundation of any organised activity and carry its business functions, so investment in fixed assets is fundamental to port construction: it accounts for a large share of total assets, and its scale therefore indicates the strength and the potential of a crossing. Given the constraints of data availability and the close link between the development of a border port and that of its host city, this paper uses the fixed asset investment of border port cities as a proxy for investment intensity at the ports themselves. The indicator is defined as the fixed asset investment of the border port city divided by the administrative land area of that city, a normalisation intended to remove the influence of city size from the evaluation.

On the output side, and in line with the definition adopted above, the strengthening of competitiveness is treated as the key result of port operation. Following the competitiveness analysis of border land ports set out in the political economy literature [12], three indicators are selected to represent output: the volume of imported and

[1] Source: compiled by the author from [14], [15], [16], [17], [18].

exported goods, the number of inbound and outbound persons, and the number of inbound and outbound transport vehicles. The resulting index system is presented in Table 2.

Table 2.

Input and output index system for the efficiency evaluation of China's border ports[1]

Category	Indicator	Symbol	Unit	Description
Input	Fixed asset investment per unit area	x_1	10,000 yuan/km²	Investment intensity of the border port city
Output	Volume of imported and exported goods	y_1	10,000 tons	Cargo handling capacity of the border port
-	Number of inbound and outbound persons	y_2	10,000 persons	Passenger flow through the border port
-	Number of inbound and outbound transport vehicles	y_3	10,000 vehicles	Vehicle flow through the border port

The fixed asset investment of the cities hosting the sample ports and the administrative land area of those cities were obtained from the China Statistical Yearbook for 2018-2022. The output indicators - the volume of imported and exported goods, the number of inbound and outbound persons and the number of inbound and outbound transport vehicles - were drawn mainly from the China Port Yearbook for the same editions, and missing values were supplemented from the official websites of the relevant provincial and municipal authorities.

China's border ports consist primarily of highway crossings, with railway ports playing a secondary role. From the thirty-two first-class border highway ports, this study retains those located in prefecture-level or county-level cities and selects the ten crossings with the highest average total import and export freight volume over 2017-2021 as the research sample. Applying the generalized DEA model for panel data and taking the comprehensive efficiency values of 2017 as the reference set, the comprehensive efficiency values for 2018-2021 were obtained; they are reported in Table 3.

Table 3.

Comprehensive efficiency values of ten Chinese border highway ports, 2018-2021 (2017 = reference set)[2]

Port (province or region)	2018	2019	2020	2021	Efficiency class
Erenhot (Inner Mongolia)	1.31	1.28	2.48	1.35	High
Laoyemiao (Xinjiang)	1.65	1.86	1.92	1.56	High
Horgos (Xinjiang)	1.00	1.00	1.00	1.00	Stable
Ruili (Yunnan)	1.00	1.00	1.00	1.82	Stable, rising
Manzhouli (Inner Mongolia)	1.00	1.00	1.00	0.83	Stable, declining

[1] Source: compiled by the author on the basis of [12].
[2] Source: calculated by the author from the China Statistical Yearbook and the China Port Yearbook (2018–2022 editions).

Port (province or region)	2018	2019	2020	2021	Efficiency class
Youyiguan (Guangxi)	0.88	0.94	1.09	0.92	Low
Dandong (Liaoning)	0.86	0.81	0.88	1.02	Low
Houqiao (Yunnan)	0.81	0.77	1.42	0.86	Low
Suifenhe (Heilongjiang)	0.92	0.83	0.70	0.91	Low
Irkeshtam (Xinjiang)	0.89	0.67	0.56	0.52	Low, declining

The computational sequence that produced these values is summarised in Figure 1. Each stage supplies the input of the next one, and the classification in the final stage rests on the interpretation rules of the D-panel model set out above.

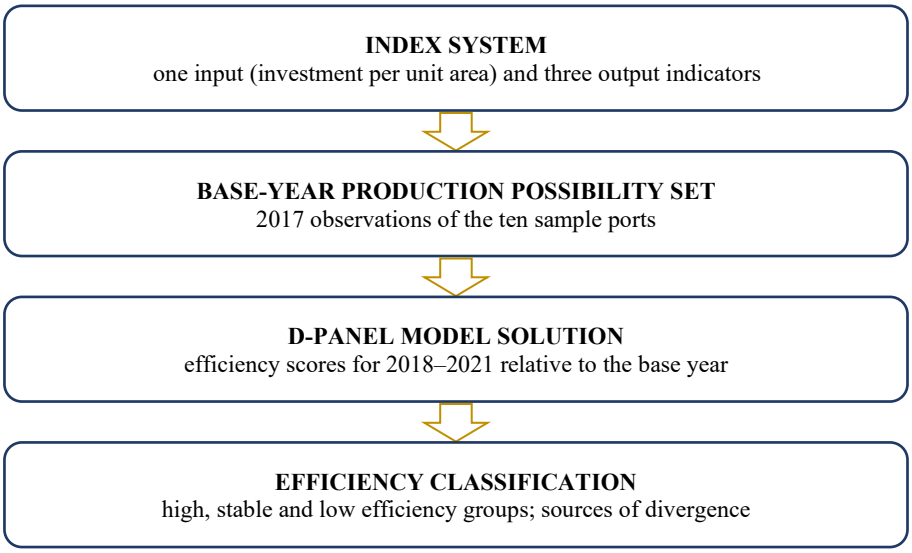

Figure 1. Sequence of the efficiency measurement procedure applied to the sample border ports[1]

The ten ports fall into three classes. The first comprises the crossings whose efficiency exceeded the 2017 reference set in every year of the period: Erenhot and Laoyemiao. Both serve as the principal border highway ports of their respective regions and handle the greater part of foreign trade cargo for the frontier provinces and cities, so fixed asset investment has produced substantial returns in competitiveness. Laoyemiao, known as the first gate of the eastern Xinjiang corridor, is a key node in the outward-oriented development of Hami City; with markedly improved infrastructure and continuing transformation of its operations, its port economy is moving towards multi-channel and diversified activity. Erenhot recorded the highest single value in the sample, 2.48 in 2020. The underlying data show that fixed asset investment per unit area fell from 100.64 to 52.96 million yuan per square kilometre, a reduction of 47.4 per cent, while the volume of imported and exported goods rose from 290,400 to 303,880 tons, an increase of 4.6 per cent. Output therefore grew while input contracted, which indicates that the strategic position of the crossing within the

[1] Source: compiled by the author on the basis of [13].

regional opening-up framework is strengthening rather than that new investment was productive.

The second class contains the ports whose scores remained at the level of the base year for most of the period: Horgos, Ruili and Manzhouli. Horgos has become the leading foreign trade crossing of Ili Prefecture and occupies an important place in the westward opening strategy; its freight volume has consistently ranked first among the national highway ports, with an average annual figure above twenty million tons, a level close to the designed capacity of the crossing. Relative to the continued increase in fixed asset investment, most of which has been directed to the renovation of machinery and equipment, the corresponding gain in competitiveness has become less pronounced, so the score remains at unity. Ruili maintained the base-year level from 2018 to 2020 and rose to 1.82 in 2021, reflecting its integration into the Belt and Road framework through improved facility support services and a more attractive investment environment, which sustained the growth of China-Myanmar trade. Manzhouli, an important gateway for China-Russia trade, held the base-year level until 2020 and fell to 0.83 in 2021: demand for the bulk commodities that pass through the crossing - chemical raw materials, iron ore and timber - has weakened, and currency movements have reduced the number of inbound shopping visitors. Where additional fixed asset investment no longer raises competitiveness, ports of this class should seek gains in soft capacity, deepening cross-border cooperation arrangements and strengthening port informatisation [10].

The third class comprises the crossings whose scores were below the reference set in most years: Youyiguan, Dandong, Houqiao, Suifenhe and Irkeshtam. At Irkeshtam the decline was continuous, from 0.89 in 2018 to 0.52 in 2021. These are long-established highway ports of the frontier provinces, and they suffer from ageing facilities and equipment and from operating procedures that no longer match traffic requirements. Some of the connecting border highways are of a low road class, which restricts any improvement in cargo handling capacity, and the supporting infrastructure for clearance, declaration and inspection remains underdeveloped, so clearance costs are high and processing times long. Evidence on clearance efficiency confirms that procedural time is itself a binding constraint on port performance [18]. For these ports, future effort should raise the utilisation rate of existing fixed assets and draw on the specific features of the host cities to develop local specialty industries, thereby avoiding redundant construction and destructive competition between neighbouring crossings.

Taken together, the results indicate that the return on port investment depends on the developmental stage of the crossing rather than on the volume of investment alone. Where capacity is far from its design limit and trade demand is growing, additional investment translates into competitiveness; where throughput has approached the design limit, further capital spending yields diminishing returns and the constraint shifts to organisational and informational capacity [9], [11]. This finding is consistent with the geographical evidence that port-city relationships evolve through distinct stages rather than along a single trajectory [7].

CONCLUSION AND SUGGESTIONS

Improving the efficiency of border ports strengthens both port competitiveness and the economy of the host city [12]. The measurement carried out here reveals a discernible gap in input-output efficiency among China's major border crossings. Ports with high operational efficiency have become new growth poles for local development, while those with low efficiency function mainly as transport corridors and lack the capacity to drive development in their urban hinterlands. Building an economic belt along the frontier therefore requires a careful assessment of each situation and cannot simply replicate the mature development model of other ports [2].

Several recommendations follow. First, investment planning should be differentiated by efficiency class: capacity expansion is justified where throughput remains below the design limit, whereas ports operating near that limit require investment in clearance technology, information systems and cooperation arrangements rather than in additional physical capacity [10]. Second, for the low-efficiency group the priority is the renewal of ageing equipment and the alignment of operating procedures with current traffic, together with the upgrading of the connecting road network, since a low road class limits handling capacity irrespective of investment inside the port [4]. Third, clearance time should be monitored as a standing performance indicator, because procedural delay raises costs without appearing in throughput statistics [18].

Fourth, port development should be coordinated with the industrial profile of the host city so that traffic generates local value added instead of merely passing through, an approach supported by the evidence on the joint evolution of port and hinterland economies [9]. Fifth, neighbouring crossings within one region should coordinate their construction programmes to avoid duplicated facilities and destructive competition [8]. Sixth, the resilience of port administration, including its capacity to maintain operations during emergencies, should be treated as a component of competitiveness rather than as a separate administrative matter [11].

The study has two limitations that indicate directions for further work. The indicator system requires additional refinement, particularly on the input side, where city-level investment serves only as a proxy for investment at the crossing itself [1]. In addition, the available statistics report the volume but not the value of the goods passing through the ports, which inevitably affects the evaluation; extending the analysis to trade value, and to railway crossings alongside highway ports, would strengthen the results [3], [5], [6].

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