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Improving customs clearance bottleneck in the Chinese B2C import cross-border e-commerce: extending sampling methods by two stages

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The rapid growth of cross-border e-commerce poses significant challenges to the labour-intensive customs clearance process. Physical inspection of contents remains a compulsory burden in the customs clearance process, even for modern customs clearance centres. This research aims to identify a sampling method for a global solution that satisfies stakeholders' interests in cross-border e-commerce in terms of accuracy, promptness, and resilience. To accomplish this, operational data were collected from a customs clearance centre in southern China to perform a realistic simulation. Further, the performance of various sampling methods was simulated based on the current simple random sampling versus various two-stage sampling methods. Pallet handling utilises two-stage sampling methods to enhance efficiency in combination with an informative sample size. Thus, an appropriate two-stage sampling method ensures optimal performance, thereby overcoming the undesirable side effects of the sampling methods. The study found that TSS1 with a sampling probability proportional to pallet size was optimal in satisfying the contradictory interests of the stakeholders. This study provides a toolset to improve the efficiency of customs clearance by applying theoretical sampling techniques to the challenges encountered in customs clearance operations. Thus, it contributes to eliminating bottlenecks in customs clearance centres in countries worldwide, which can lead to the global success of cross-border e-commerce.

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Introduction

Numerous China-based Cross-border e-commerce (CBEC) platforms, such as AliExpress and Temu, dynamically provide price-competitive goods to consumers worldwide. Furthermore, the purchasing power of Chinese consumers has rapidly increased, along with annual growth in direct purchases of high-tech and luxury goods (Willersdorf et al., 2020). Notably, China's increasing CBEC imports emerged as a key growth engine for the global consumer market during COVID-19 (Bowman, 2022; Deloitte, 2019). The advancement of CBEC in China has led to reduced timelines in the logistics facilitation measures in the marine and land transport infrastructure (Liang et al., 2021). However, the delay in customs clearance (Liu et al., 2021), considered uncontrollable, generates bottlenecks, posing as an obstacle to the adoption of CBEC. Hitherto, little attention has been paid to addressing bottlenecks in customs clearance centres.

The purpose of customs clearance centres is to promote public welfare and business efficiency. The customs clearance operation involves three main stakeholders: online shoppers, customs authorities, and warehouse logistics service providers (LSPs) that work for the customs authorities. From the online shoppers' perspective, the prompt processing of their shipment in customs clearance is critical (Niu et al., 2019). However, this is often delayed because of the sudden suspension of customs clearance. From the customs authorities' perspective, precise taxation (Faccia and Mosteanu, 2019) and supervision of trade security (Song et al., 2019) are paramount. From the LSPs' perspective, efficient operation is vital in managing the customs clearance centre on behalf of the customs authorities. Therefore, LSPs aim to reduce manual workload to increase profits and strengthen operational flexibility. However, customs clearance operations are often subject to diverse incoming volumes or indifferent policies such as inspection rate regulations. The operational purpose of the customs clearance centre is illustrated in Fig. 1.

This study aims to identify a sampling method for meeting the requirements of the three stakeholders. Hence, the following three research questions are proposed:

RQ1. How can content-check results be made more accurate and consistent? (accuracy)

RQ2. How can the duration of the consumer box stay in the customs clearance centre be shortened? (promptness) RQ3. How can content-check time be saved in stressful environments? (resilience)

Customs clearance operations consist of two steps: quantity and content checks. The first step involves reviewing and validating the declaration of the imported goods by inspecting them using barcode scanners. LSPs use radio-frequency identification (RFID) scanning equipment or barcode scanning conveyors to improve checking efficiency (Baashirah and Elleithy, 2019). The second step is validating the contents for risk management—a security check for prohibited items such as dangerous goods and drugs (Widdowson, 2020) and a commercial check for tax evasion or concealment (e.g. luxury goods). Security checks can be conducted using X-rays. However, a commercial check should be followed by a physical inspection of boxes sampled using simple random sampling (SRS) from the disassembled boxes on the conveyor belt. Owing to its labour intensity, it is often considered a black box bottleneck (Guercini et al., 2020).

This study was motivated by a real-life process innovation project that improved the bottleneck depicted in Fig. 2. The recent development of X-rays allows security checks at the pallet level without disassembling the pallet. The commercial check introduces two-stage sampling (TSS), in which the pallets are sampled first, and subsequently, from these sampled pallets, a few boxes for physical inspection are sampled. Although it saves time in the disassembling of pallets, it is associated with the side effects of TSS, such as cluster effects in selecting a pallet instead of an individual box. Thus, considering the cluster effects, a TSS method is recommended.

This study utilised a discrete event simulation based on stochastic parameters from a real-life customs clearance centre in China. It contributes to the extant literature by providing a concrete solution for emergent cross-border e-commerce bottleneck issues, supported by rigorous validation utilising TSS theory. This research will assist China and other countries at comparable stages or using similar customs clearance methods to enhance the efficiency in their customs clearance.

Literature review

In principle, world trade is fuelled by efficient customs operations (Ibrahim and Ajide, 2022). Among the trading parties, the trade cost can be reduced with efficient customs operations (Çelebi, 2022). Consequently, tariff evasion can be minimised for those countries' borders (Beverelli and Ticku, 2022). Therefore, upon recognising the significance of efficient customs clearance, many countries try to improve their customs operations at seaports or airports (Kornher et al., 2024). Simplifying customs procedures for goods transit has multiple benefits, such as increased trade activity (Shikur, 2022), reduced bureaucratic border hindrances, and decreased administrative costs (Rbehat and Marafi, 2024). The focus of enhancing customs operations varies with technology, human resources, government policies, and procedures. Owing to their different needs and economic developments, various countries have made distinct efforts to enhance customs clearance. Modernisation initiatives hold significant potential to benefit emerging and developing countries (Omosa, 2022). The key areas of research depend on the strength of the customs clearance centre's regions. Asia focuses on technology, whereas Europe is more procedure-centric (Table 1).

Technology can provide breakthroughs for linear improvements in customs operations. European countries and Australia have established an electronic document interface between customs authorities and major e-commerce platforms to automate

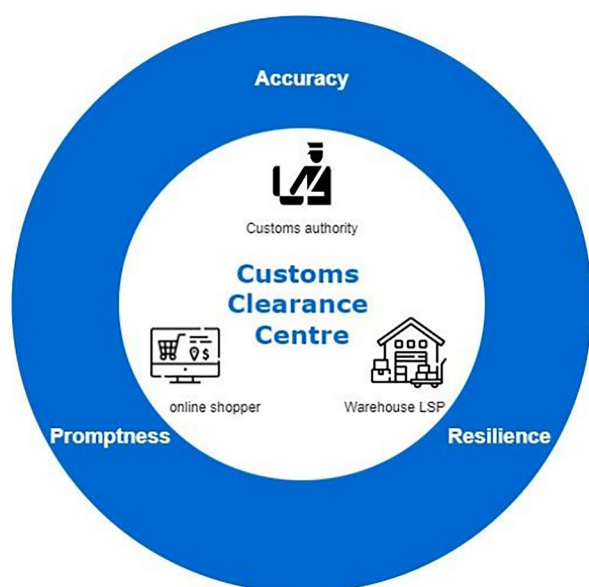
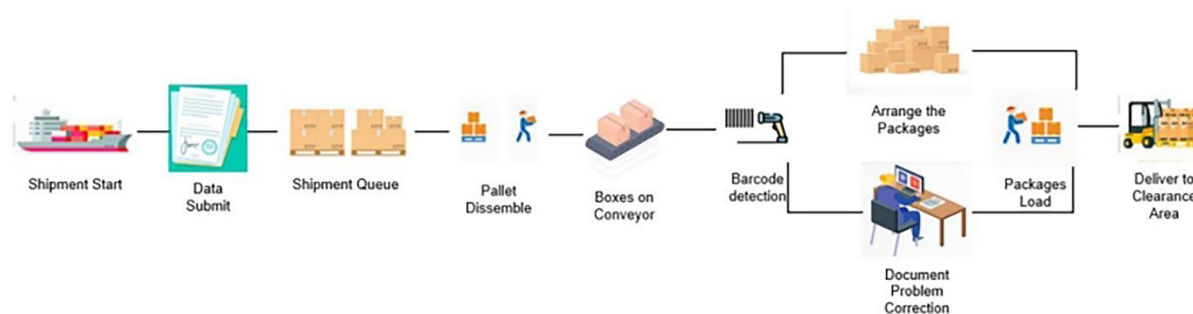
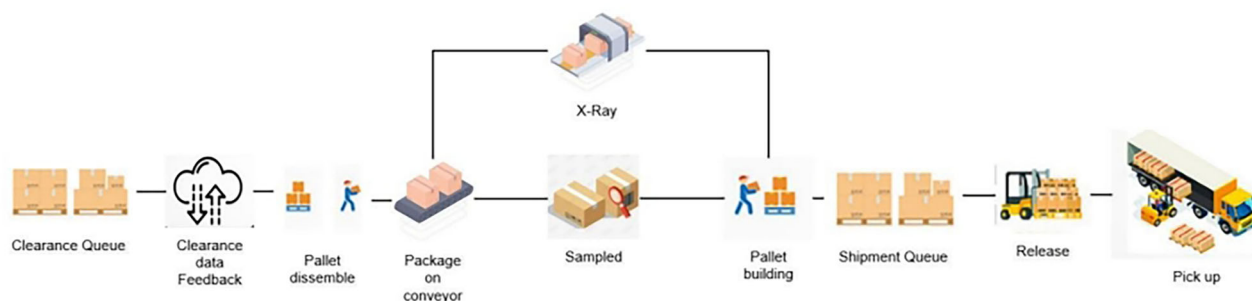


Fig. 1 The illustration presents the various operational purposes of three stakeholders in customs clearance centres. Source: Authors' own elaboration.

I. Quantity check against the declaration



II. Contents check against the declaration (SRS)



III. Contents check against the declaration (TSS)

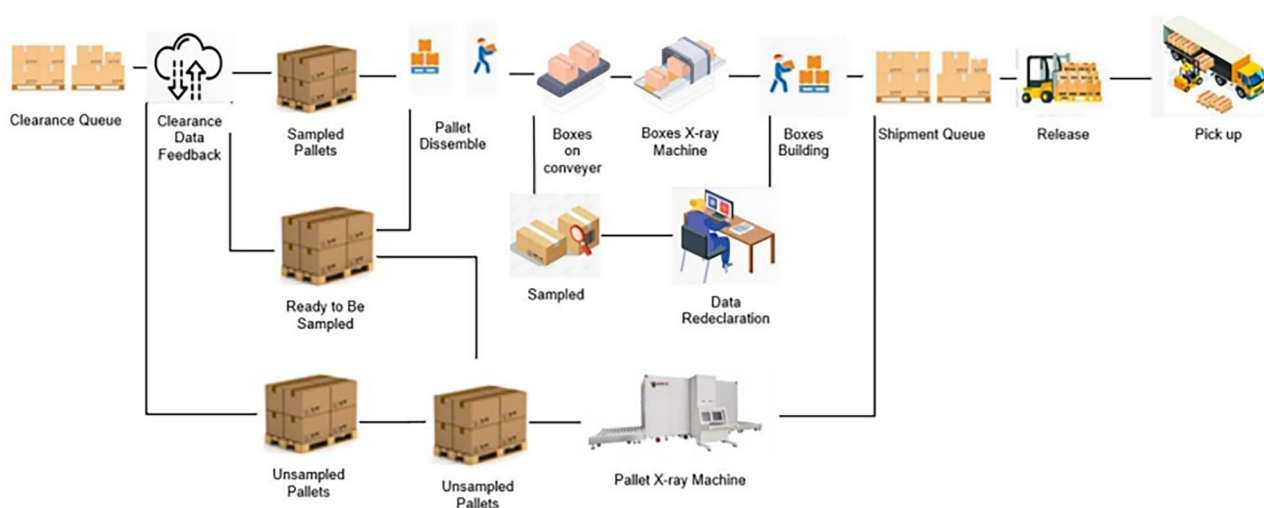


Fig. 2 The diagram illustrates the customs clearance process, which involves both quantity checks and content checks. It especially contrasts the distinctive contents check after adopting pallet X-rays equipped with two-stage sampling methods. Source: Authors' own elaboration.

customs risk management and evaluate supply chain risk (Fang and Wang, 2021). Most recently, blockchain technology has streamlined and automated customs processes, enhancing the efficiency, transparency, and reliability of international business transactions (Pesquera, 2024). Yan (2024) designed a hierarchical blockchain structure, creating a customs supervision platform that reads data for hierarchical processing, demonstrating efficient and sustainable trade development. Scholars indicate that introducing artificial intelligence technology in the customs

regulatory process opens new opportunities for the customs regulatory framework (Vovchenko et al. 2022). Yang (2022) found that RFID technology is advantageous for obtaining necessary customs information for efficient logistics clearance. According to Gao and Kuang (2023), the automation of customs operations by robotics provides new risk management insights for customs data regulatory analyses and other collaborative departments. Gao et al. (2023) acknowledge that advanced customs clearance systems could support the clearance of goods at

Table 1 The overview of the literature on the research problems of customs operations.				
Area	Technology	Human Resource	Government Policy	Procedure
General	Pesquera (2024)			Hiraide et al. (2022) Desiderio (2019) Hu et al. (2023) Danladi et al. (2024) Caballini and Benzi (2023) Liang et al. (2021) Ding et al. (2022)
Europe	Vovchenko et al. (2022) Gao et al. (2023) Lebid et al. (2021)	Shpak et al. (2020)		
Oceania	Fang and Wang (2021)			
Asia	Yan (2024) Yang (2022) Gao and Kuang (2023) Nguyen et al. (2021)	Hua (2022) Sanjahaya Jahir et al. (2024)	Chen et al. (2022) Xinhua (2022) Van Asch et al. (2020)	Chang et al. (2019)
Africa	Tadesse et al. (2022) Addo (2022)	Tadesse et al. (2022)	Konstantinus and Woxenius (2022) Tadesse et al. (2022) de Melo et al. (2024)	Ayesu et al. (2024)

This table reports the structural analysis of research problems in the literature on customs clearance operations. Source: Authors' own elaboration.

any transit point in the global supply chain. In Ukraine, customs authorities use digitalisation to simplify customs procedures for increasing efficiency (Lebid et al. 2021). In Ghana, the customs department has introduced paperless customs clearance (Addo, 2022). Vietnam’s customs authority is currently evaluating the efficiency gains from using an e-customs portal (Nguyen et al., 2021).

Customs human resource management directly affects the efficiency of customs clearance. With the constant evolution of the modern customs environment, a progressive customs system is necessary to overcome various challenges (Shpak et al., 2020). Upon examining the construction of customs human resources, Hua (2022) put forward five suggestions. First, define the types of customs experts. Second, extensively participate in international customs activities and learn the customs system of other countries. Third, deeply examine the system of docking between professional and technical civil servants and customs experts. Fourth, improve the relevant system arrangement of expert leadership, and clarify the hierarchy of expert leadership. Finally, actively explore the use of expert teams. This approach is followed by the Indonesian customs that addresses bureaucratic inefficiencies, transparency issues, technological integration, and regulatory enforcement (Sanjahaya Jahir et al. 2024).

The government’s customs clearance policies significantly affect CBEC and infrastructure construction (Chen et al. 2022). The Chinese government set up 27 CBEC pilot zones, implementing a bonded warehouse stock system model with strict supervision (1210 supervision mode) for facilitating the fast-growing e-commerce volume of consumers’ direct orders in China (Xinhua, 2022). Furthermore, it implemented ‘direct mail mode’ customs clearance centres (9610 supervision mode) for faster and safer customs clearance for individually purchased items (Van Asch et al., 2020). For Africa, which is relatively underdeveloped, effective trade agreements can help reduce customs clearance of goods imports by at least 3.7 days (de Melo et al., 2024). However, there is still a need for further coordination between policy and its implementation via practical procedures (Konstantinus and Woxenius, 2022).

Hiraide et al. (2022) emphasised the reform of customs procedures by enhancing customs administration and inspections. For example, a single point of contact between operators and the government significantly enhances trade performance in many countries by saving communication time. For more reliable customs operations, the customs authority, as a public administration, should be under supervision through an appeals procedure

involving all supply chain parties (Hu et al., 2023). Additionally, customs clearance efficiency, measured by speed, simplicity, and predictability, is considered an important logistics performance index. It examines the competitiveness of international trade, focusing on optimising customs procedures and cooperating with stakeholders to enhance customs clearance processes and facilitate trade flows (Ding et al., 2022). Therefore, this study designed a customs clearance procedure that addresses the issue of customs operations on the floor. By contrast, most studies to date (Ayesu et al., 2024; Caballini and Benzi, 2023; Chang et al., 2019; Danladi et al., 2024; Desiderio, 2019) have only evaluated the relationship between the factors influencing customs procedures from a high-level perspective. Unfortunately, these methods prove inadequate for providing concrete solutions in terms of operational proficiency in the customs clearance procedure. Furthermore, few studies have extended their scope to include comprehensive logistics models (Giuffrida et al., 2020; Wang et al., 2021).

Therefore, by addressing the sampling method used in current operations, this study aims to fill the gap in improving tangible customs clearance efficiency. This research used a discrete event simulation by modelling a real-life operation in China to verify the assumptive solutions in sampling. This approach can address practical problems shared by customs authorities globally, improving the effectiveness of customs operations (e.g., accuracy and speed) and enhancing the efficiency of economic resource usage.

Methodology

Figure 2 explains the physical inspection of the content check process. The current customs clearance sampling method is SRS, that is, single-stage sampling directly from the population, which helps in reducing sampling bias. Theoretically, this method is simple to understand; however, it is often difficult to implement practically and efficiently when working with a large sample (Lohr, 2021). Our case also takes excessive time due to the manual labour required to disassemble the pallets into individual boxes, before the boxes are randomly sampled on the conveyor. Therefore, instead of boxes, limited pallets are sampled first. Subsequently, the boxes for physical inspection are sampled from the selected pallets, given that the pallet X-rays are adopted efficiently for security checks. This study suggests a TSS design: pallet sampling (first stage), and box sampling (second stage). Thus, it exempts the unselected pallets in the first stage from the costly unloading and loading of packages.

However, the TSS method raises concerns about sampling quality, known as cluster effects, which may introduce bias due to

Table 2 The logic of the sampling methods.

		1st stage Sampling rule			2nd stage Sampling rule		
		Select pallets among Population pallets ($N \rightarrow n$)			Select boxes among the sum of the boxes in Selected pallet i ($M_i \rightarrow m_i$ or f)		
		Total Population Units (pallet)	Total Sampled Units (pallet)	the probability in selection of the Pallet	Total Population Units (box)	Total Sampled Units (box)	the probability in selection of the box
Single-Stage Sampling	SRS	N/A			M	m	$\frac{1}{M}$
Two-Stage Sampling	TSS1	N	n	$\frac{M_i}{M}$	M_i	f^a	$\frac{1}{M_i}$
	TSS2	N	n	$\frac{1}{N}$	M_i	m_i^b	$\frac{1}{M_i}$
	TSS3	N	n	$\frac{1}{N}$	M_i	f^a	$\frac{1}{M_i}$

^a f is a fixed number, the same as m/n , due to the fair comparison condition.

^b m_i is a proportionate number as $p \cdot M_i$ s.t. p is the same as m/M due to the fair comparison condition.

Source: Authors' own elaboration.

the grouping in the first stage. Taconeli and Cabral (2019) proposed a new TSS design based on neoteric ranked set sampling. Their proposed sampling designs outperformed previous methods because they produced a smaller mean-square error for the estimator of the population mean. Recently, Innocenti et al. (2021) considered three different TSS designs when the cluster size varied within a population. They compared the efficiencies of the three TSS designs with those of the simple random sampling methods. Additionally, they derived an optimal design for each TSS scheme by minimising the sampling variance of the population mean estimator under budget constraints.

Therefore, if the cluster size is known prior to sampling, an appropriate strategy can be suggested for designing a TSS to address our research questions. This study proposes the best TSS methods with optimal quality by ensuring minimum cluster effects and maximum efficiency as well as the shortest processing time in the customs clearance centre. The recommended TSS method is validated by comparing the simulation results with TSS designs, similar to those of the original SRS methods.

Modelling of the sampling methods. Daily operations in the customs clearance centre commence with the arrival of shipments that consolidate multiple consumer boxes. These boxes are first consolidated by pallets and subsequently by shipments that are delivered in one batch. Thus, the model's data structure comprises three levels (Snijders and Bosker, 2011).

K = total number of shipments in the population, with index set $K = \{1, 2, 3, \dots, K\}$ (1)

N = total number of pallets in the population, with index set $I = \{1, 2, 3, \dots, N\}$ (2)

M = total number of boxes in the population, with index set $J = \{1, 2, 3, \dots, M\}$ (3)

m = number of boxes in the sample, sampled index set $S_B \subseteq J$ with $|S_B| = m$ (4)

The SRS method samples the final units based on the sampling rate policy r . Thus, the total number of boxes m is selected from the overall M population of boxes. Sampling from the customs

authority perspective identifies a few noncompliant boxes and the population's noncompliance rate. The noncompliance of individual boxes, y_{ijk} , with indices i, j , and k (for pallet, box, and shipment, respectively), given the sampling rate policy r , is as follows:

$$r = m/M \quad (5)$$

$$y_{ijk} = 1 \text{ for a noncompliant box, otherwise } 0 \forall i \in I, j \in J, k \in K \quad (6)$$

In this study, we introduce a TSS model to model shipments with the total number of pallets N and the total number of boxes M . In the first stage, n pallets are selected from N pallets. In the second stage, the total number of sampled boxes, m , is selected from the total number of selected pallets, n , from the 1st stage. Each pallet has a different number of boxes; the number of boxes from a selected pallet i in the first stage is M_i , and the number of boxes from a selected pallet i in the second stage is m_i . Thus, the following notations exist in the two-stage sampling:

n = number of pallets selected during the first stage, let S_p be the index set of sampled pallets, where $|S_p| = n$ (7)

M_i = total number of boxes contained in selected pallet i at the first stage, $\forall i \in S_p$ (8)

m_i = number of boxes sampled from pallet i during the second stage, $\forall i \in S_p$ (9)

Hence, the noncompliance rates of the population and TSS sample, Y and y , can subsequently be expressed as follows:

$$Y = (1/M) * \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J y_{ijk} \forall i \in I, j \in J, k \in K \quad (10)$$

$$y = 1 / \left(\sum_{i=1}^n m_i \right) * \sum_{k=1}^K \sum_{i=1}^n \sum_{j=1}^{m_i} y_{ijk} \forall i \in S_p, j \in S_B, k \in K \quad (11)$$

In the sampling theory (Levy and Lemeshow, 2013), three types of TSS are often introduced: TSS1, TSS2, and TSS3. The sampling logic is presented in Table 2.

As a baseline, SRS is a single-stage sampling method with only one direct selection from the disassembled boxes of the conveyor belt. Therefore, the SRS selects the final unit, m , from the

population box, M , indifferently, ensuring an equivalent probability for selecting a final unit $1/M$. No clusters exist in the sampling procedure; therefore, there is no cluster effect.

The first TSS is TSS1, where we sample the primary units (pallets) using a fixed number of pallets (n) from the population pallets (N) and subsequently sample a fixed number of boxes (f) from each selected pallet. For a fair comparison, m is similar to $n \times f$ (i.e. $f = m/n$). The sampling rule assigns a probability of selection to each unit per stage. We first select each primary unit with a probability proportional to the cluster size M_i for each pallet i . Thus, the greater the pallet size, the greater the selection probability in the first-stage sampling, given by M_i/M . We subsequently select the fixed number of boxes f from each pallet chosen from the previous sampling. Here, the probability of selecting the final units is uniform among m boxes, given by $1/M_i$.

The second TSS is TSS2, which samples n primary units (pallets) from N clusters with a uniform probability $1/N$. Thereafter, it selects the differentiated numbers of boxes, m_i for $i \in S_p$ by applying the ratio, p , which is the ratio of m to M , because we need the same final unit, m , at the end for a fair comparison among the four sampling methods. The selection of boxes follows an equal probability, that is $1/M_i$, between the boxes in pallet i , for $i \in S_p$.

The last TSS, TSS3, samples pallets and boxes (i.e. n and f , respectively) with equal unit selection probabilities, that is, $1/N$ for pallets and $1/M_i$ for boxes. This method is the simplest of the three TSS methods.

Performance measures of the sampling methods. This study used two performance measures to compare the best sampling methods for the customs clearance centre.

Quality of the sampling method. The first measure is the quality of the sampling method, which is of interest to customs authorities. The higher-quality sampling method ensures minimum side effects to avoid incorrect estimation of the noncompliance level in the population Y . This side effect is called the cluster effect, denoted by u_{ik} for pallet i in shipment k . This arises due to clustering (pallet) in the first stage of the TSS, in contrast to the SRS. If the noncompliance rate of the sampled boxes in a TSS is defined as y_{ijk} , it can be formulated as follows:

$$y_{ijk} = \beta_0 + u_{ik} + \varepsilon_{ijk} \quad \forall i \in I, j \in J, k \in K \quad (12)$$

where β_0 is the expected noncompliant value in the case of no sampling effects (u_{ik}) and no individual noise (ε_{ijk}).

This study addresses the research question on quality performance using the absolute difference in the noncompliance rate between the original Y (population) and the measured y (sample) using various sampling methods (SRS, TSS1, TSS2 and TSS3). The leading cause of this difference in the noncompliance rate is attributed to the cluster effect, which is unavoidable in multistage sampling methods. During operation, the sum of the randomly generated shipments represents the population. Therefore, the formulation of the cluster effect for a specific shipment k (u_k) is as follows:

$$u_k = \text{abs}(Y - y)/Y \quad \forall k \in K \quad (13)$$

Sampling method efficiency. The second measure regarding the efficiency of the sampling method concerns online shoppers and logistics service providers. An efficient sampling method leads to a lower average duration of boxes ($\bar{T}_B$) in the customs clearance process. The boxes are consolidated by shipment using a batch procedure, and the duration time (T_k) is first measured by shipment. T_k is the time duration from the entrance of the shipment into the customs clearance centre to the release of the

shipment from it. It is subsequently divided by the sum of the number of sampled boxes, m , during the operation time. For a fair comparison across sampling methods (SRS, TSS1, TSS2 and TSS3), m was aligned to be the same. The efficiency of the sampling method is expressed as follows:

$$\bar{T}_B = \left(\frac{1}{m}\right) \sum_{k=1}^K T_k \quad \forall k \in K \quad (14)$$

Descriptive analysis of the simulation data. This study collected operational data from a customs clearance centre in southern China to perform a realistic simulation. The data includes statistics on the number of shipments, pallets per shipment, boxes per pallet, and noncompliance rate. Although we applied the same mean number of boxes per pallet (M/N) for the populations, we aimed for a standard deviation for the M/N variation, resulting in various coefficients of variance $CV_{M/N}$ ranging from 0 to 0.5. This variation in the $CV_{M/N}$ provides a rigorous test of the research findings. A discrete simulation software (AnyLogic 8.3) was used to obtain a probability distribution on the collected statistics for data simulation. A descriptive analysis was conducted during 70 days of operation to ensure the stability of the randomly generated daily data. An overview of the descriptive analysis of the generated populations is presented in Table 3.

Table 3 shows that the change in n of $CV_{M/N}$ from 0 to 0.5 generated six groups of population datasets. The mean values of $CV_{M/N}$ obtained were 0.1, 0.19, 0.29, 0.37, and 0.44, indicating that the data generated on $CV_{M/N}$ were as expected. Other measurements, such as the number of shipments, pallets per shipment, boxes per pallet, and noncompliance rates, align with the intended statistics from the benchmark customs clearance centre.

We applied four sampling methods: SRS, TSS1, TSS2, and TSS3 as per the sampling strategy indicated in Table 2. We generated a series of sampling data from the aforementioned populations using a discrete simulation software (AnyLogic 8.3). Table 4 presents a descriptive analysis of the sampling data.

The number of boxes per pallet was the highest for TSS1 because the probability of selecting the pallet in the first stage increased linearly with the number of boxes in the pallet. However, the number of selected pallets in the first stage and the total sum of the selected boxes in the second stage were found to be the same for the different sampling methods, reflecting a similar sampling rate (m/M) of 4.29%.

Results

Sampling methods accuracy. We can assess the accuracy of the sampling methods based on the quality performance index, defined as the cluster effects in Eq. (13). Furthermore, from a quality control perspective, it is significant to assess the performance consistency in terms of standard deviation and the performance level relative to the mean value. For more generic experiments, we measured the cluster effect of the sampling methods in different populations with various coefficients of variance for the number of boxes on pallets (M/N). The means and variances of the cluster effects are summarised in Table 5.

The noncompliant rates in the populations were found to be similar at 16.5%. When starting from the population with $CV_{M/N} = 0$ (uniform number of boxes per pallet), the mean and standard deviation of the cluster effects are similar across the sampling methods. With an increase in $CV_{M/N}$, TSS1 outperforms all the other sampling methods, such that the mean and standard deviation of the cluster effect are indicated at the lowest level (Table 5). Therefore, this implies that TSS1 delivers the least cluster effect with consistency, detecting noncompliant packages in accordance with the population's noncompliance rate.

Table 3 The descriptive analysis of simulation data (Populations).

Data	Descriptive details	CV _{M/N} (0)	CV _{M/N} (0.1)	CV _{M/N} (0.2)	CV _{M/N} (0.3)	CV _{M/N} (0.4)	CV _{M/N} (0.5)
Populations	Total # of shipments ^a (K)	Sum of Shipments	533	488	525	531	534
	Pallet per shipment ^b (N)	Mean of N (μ_N)	16.77	16.58	16.29	16.38	16.49
		Standad deviation of N (σ_N)	4.06	3.99	4.14	4.02	4.01
	Boxes per Pallet ^c (M/N)	Mean of M/N, ($\mu_{M/N}$)	100.00	99.20	99.69	99.71	99.30
		Standad deviation of M/N ($\sigma_{M/N}$)	-	9.93	19.30	29.07	37.08
		Coefficient of Variance ^d (CV _{M/N})	-	0.10	0.19	0.29	0.37
	Non compliance rate ^e (Y)	Mean of Y (μ_Y)	16.52%	16.48%	16.52%	16.52%	16.54%
		Standad deviation of Y (σ_Y)	0.95%	0.94%	0.97%	1.00%	1.01%

^aPoisson Arrival random distribution ($\lambda = 7.60$ /daily arrival for 70 operation days).
^bUniform random distribution (min: 10, max: 24).
^cNormal random distribution (μ : 100, σ : 10).
^dCoefficient of Variance for M/N is calculated by $\sigma_{M/N}/\mu_{M/N}$.
^eNormal random distribution (μ : 16.5%, σ : 1%).
Source: Authors' own elaboration.

However, the worst-performing sampling method was TSS2, with the largest mean and standard deviation of the cluster effect. The performance difference between TSS1 and the worst methods increased as CV_{M/N} increases from 0.0 to 0.5, indicating an increase in the diversity in the number of boxes per pallet.

The results depicted in Table 5 are based on randomly generated data in the simulation model with operational parameters. Thus, the comparison results should be examined for robustness. To this end, we used an independent sample t-test for each pair of sampling methods concerning the means and variance of the cluster effects. We repeated the t-test with different CV_{M/N} populations. The results are presented in Table 6.

T-test results. Table 6 highlights the significant differences among the sampling methods at the 1%, 5%, and 10% significance levels. At the population of CV_{M/N} 0, no statistically significant differences were observed, whereas at the population of CV_{M/N} 0.1, the ranking of the mean clustering effect was TSS1 < TSS3 < SRS < TSS2, with a significant difference between TSS1 and TSS2. The rank of the standard deviation of the clustering effect was similar to that of the mean. However, no significant difference was observed for the standard deviation. At the population of CV_{M/N} 0.2, the mean ranking of the clustering effect was TSS1 < TSS3 < SRS < TSS2, and the differences between TSS1 and SRS, TSS2 and TSS1, and TSS3 and TSS2 were significant. At the population of CV_{M/N} 0.3, the ranks for the means and standard deviations were similar to those at CV_{M/N} 0.2. Further, the standard deviation difference between TSS2 and TSS3 was significant, and the significance levels were enhanced overall. At the population of CV_{M/N} 0.4, the rank of the mean of the clustering effect was TSS1 < SRS < TSS3 < TSS2 and a significant difference was observed between TSS2 and SRS; TSS2 and TSS1; TSS3 and TSS2. The rank of the standard deviation of the clustering effect was TSS1 < TSS3 < SRS < TSS2. Further, significant differences were noted between TSS2 and TSS1, and TSS3 and TSS2. At the population of CV_{M/N} 0.5, the ranking of the mean clustering effect was TSS1 < SRS < TSS3 < TSS2, with a significant difference observed between TSS2 and TSS1. The rank

of the standard deviation of the clustering effect was TSS1 < TSS3 < SRS < TSS2, with significant differences between TSS1 and SRS and TSS2 and TSS1. These results are summarised and illustrated in Fig. 3. Thus, TSS1 outperforms the other methods in terms of the mean and standard deviation of the cluster effect, ensuring optimal quality.

Sampling methods' promptness. To measure the efficiency of the sampling methods, we define the duration per box as described by Eq. (14). In populations with varying coefficients of variables, we ran a discrete simulation model for the same period as the quality measurement. We calculated the mean and standard deviation of the duration of each sampling method (Fig. 4).

The majority of the time savings are attributed to the changed process that excludes the general pallet-disassembling steps in the SRS (Fig. 2). Instead, the TSS method conducts pallet disassembly selectively for the sampled pallet in the first stage. Thus, a significant difference exists between SRS and other TSS methods. We found that TSS1 demonstrated the highest sampling accuracy, which is of interest to customs authorities. By contrast, TSS1, TSS2, and TSS3 improved the promptness of the individual boxes compared to SRS. With the increase in the coefficient of variance for the number of boxes per pallet, the mean and standard deviation of the duration were found to be consistently smaller for the TSS methods. Among the TSS methods, TSS1 exhibited the longest duration. This can be logically comprehended from the fact that TSS1 chooses pallets with a higher number of boxes compared to other methods in the first stage. Thus, the number of sampled boxes per pallet was the highest for TSS1 (Table 4). However, the difference between the TSS and SRS sets is marginal (Fig. 4). By combining the accuracy of the test results, TSS1 is recommended as the most suitable sampling method for process innovation cases involving new X-ray machines (Fig. 2).

Sensitivity tests for the performance of the sampling methods. Ultimately, the operations in the customs clearance centre are carried out by the final stakeholder, which is the warehouse LSP.

Table 4 The descriptive analysis of simulation data (samples).																										
Data for a shipment		Descriptive details	CV _{M/N} (0)				CV _{M/N} (0.1)				CV _{M/N} (0.2)				CV _{M/N} (0.3)				CV _{M/N} (0.4)				CV _{M/N} (0.5)			
			SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3
1st Stage	# of sampled Pallets (n)	Mean	6.0	6.0	6.0	6.0	6.1	6.1	6.1	5.9	5.9	5.9	5.9	6.0	6.0	6.0	6.0	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	
		Standard deviation	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7	
	# of sampled Boxes per pallet (M/n)	Mean	-	100.0	100.0	100.0	-	108.9***	99.0	99.2	-	118.9***	99.8	100.3	-	128.7***	99.5	99.5	-	136.7***	98.6	100.0	-	145.4***	99.9	101.6
	Standard deviation		-	-	-	-	3.6	4.3	4.4	-	7.4	8.1	8.6	-	10.3	12.2	12.0	-	14.1	17.4	16.9	-	15.9	18.9	18.8	
2nd Stage	# of sampled Boxes ^a (m)	Mean	72.5	72.5	72.5	72.5	70.0	70.0	70.0	70.0	70.2	70.2	70.2	70.5	70.5	70.5	70.5	70.8	70.8	70.8	70.8	71.7	71.7	71.7	71.7	
		Standard deviation	17.4	17.4	17.4	17.4	16.8	16.8	16.8	16.8	16.8	17.9	17.9	17.9	17.9	17.9	17.9	17.9	18.9	18.9	18.9	18.2	18.2	18.2	18.2	
Underline values indicate mean values.																										
^a The sampling rate (m/M) is aligned as a single rate across the sampling methods (4.29%).																										
***for p < 0.01, **for p < 0.05, *for p < 0.10 (ns: non-significant by two-tails). Source: Authors' own elaboration.																										

Table 5 The overview of the quality performance.																									
Quality performance of samplings		CV _{M/N} (0)				CV _{M/N} (0.1)				CV _{M/N} (0.2)				CV _{M/N} (0.3)				CV _{M/N} (0.4)				CV _{M/N} (0.5)			
		SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3
Non compliant rate (Y) in the population	mean of Y	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.5%	16.6%	16.6%	16.6%	16.6%	
	std of Y	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	
	Y	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	
Non compliance rate (Y) in the sample	mean of Y	16.2%	15.4%	15.3%	15.4%	15.4%	15.7%	15.6%	15.4%	16.5%	15.6%	15.6%	15.5%	15.4%	16.5%	15.7%	15.6%	15.7%	16.5%	15.9%	15.8%	15.9%	15.8%	15.8%	
	std of Y	5.1%	4.7%	4.7%	4.3%	4.8%	4.4%	4.9%	4.6%	5.1%	4.4%	4.9%	4.9%	4.5%	5.4%	4.5%	5.1%	4.7%	5.0%	4.6%	5.1%	4.6%	5.2%	4.8%	
	Y	4.01%	4.04%	4.00%	3.98%	3.84%	3.64%	4.06%	3.76%	4.02%	3.65%	4.07%	3.74%	3.74%	4.07%	3.66%	4.19%	3.83%	3.80%	3.74%	4.22%	3.83%	3.85%	3.87%	
Cluster effects ^a (u)	mean of u	2.99%	2.92%	2.87%	2.74%	2.92%	2.80%	2.97%	2.99%	2.96%	2.70%	2.85%	2.70%	2.85%	3.21%	2.85%	3.33%	2.88%	3.08%	2.79%	3.20%	2.90%	3.28%	2.94%	
	std of u																								
aThe lowest Cluster effects (u) among the sampling approaches is underlined.																									
Source: Authors' own elaboration.																									
All column numbers are percentages.																									

Table 6 The robust test of the quality performance.

Quality Performance difference ^a		Cluster effects mean				Cluster effect variance			
Significance ^b		SRS	TSS1	TSS2	TSS3	SRS	TSS1	TSS2	TSS3
CV _{M/N} (0)	SRS		0.880	0.944	0.159		0.908	0.778	0.152
	TSS1	−0.151		0.821	0.178	0.013		0.866	0.178
	TSS2	0.071	0.226		0.232	0.079	0.029		0.231
	TSS3	2.043	1.798	1.432		2.050	1.819	1.437	
CV _{M/N} (0.1)	SRS		0.290	0.232	0.708		0.343	0.507	0.770
	TSS1	1.059		0.023**	0.506	0.900		0.104	0.219
	TSS2	−1.197	−2.272		0.120	0.440	2.653		0.720
	TSS3	0.375	−0.665	1.556		0.085	1.511	0.129	
CV _{M/N} (0.2)	SRS		0.032**	0.811	0.113		0.039**	0.437	0.465
	TSS1	2.149		0.020**	0.594	4.258		0.006***	0.176
	TSS2	−0.239	−2.323		0.076*	0.604	7.548		0.138
	TSS3	1.587	−0.533	1.777		0.535	1.831	2.201	
CV _{M/N} (0.3)	SRS		0.027**	0.558	0.196		0.045**	0.507	0.155
	TSS1	2.214		0.005***	0.333	4.023		0.008***	0.512
	TSS2	−0.586	−2.788		0.060*	0.440	7.121		0.035**
	TSS3	1.294	−0.969	1.883		2.027	0.430	4.437	
CV _{M/N} (0.4)	SRS		0.742	0.024**	0.868		0.185	0.142	0.288
	TSS1	0.329		0.007***	0.607	1.762		0.004***	0.814
	TSS2	−2.257	−2.681		0.031**	2.159	8.520		0.010**
	TSS3	−0.166	−0.514	2.159		1.132	0.055	6.740	
CV _{M/N} (0.5)	SRS		0.243	0.124	0.904		0.024**	0.857	0.209
	TSS1	1.168		0.004***	0.171	5.109		0.009***	0.283
	TSS2	−1.539	−2.860		0.134	0.032	6.939		0.123
	TSS3	−0.120	−1.370	1.499		1.579	1.156	2.383	

^aThe statistical values for the t-test are indicated under the diagonal, and the p-values are indicated the upper diagonal.

^b*** for $p < 0.01$, ** for $p < 0.05$, * for $p < 0.1$, else for non-significant in terms of two-tails of the significance level.

Source: Authors' own elaboration.

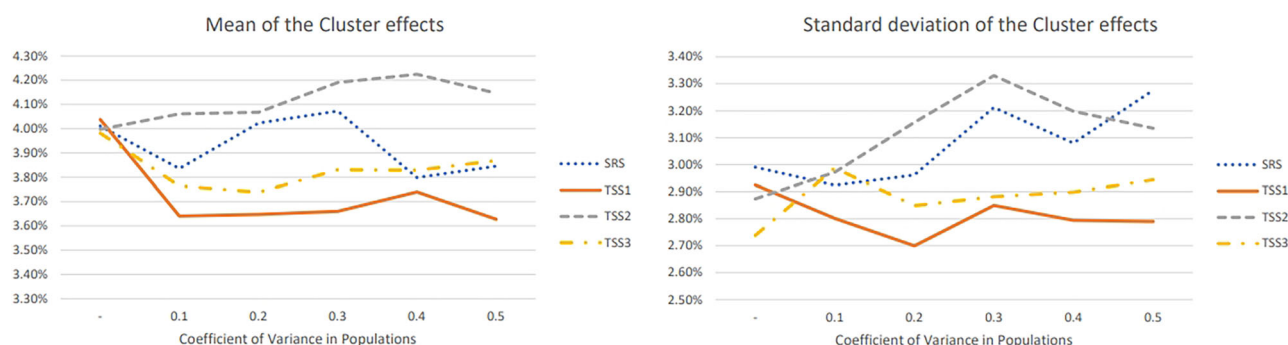


Fig. 3 The plot presents the means and standard deviations of the accuracy performance among the four sampling strategies. Source: Authors' own elaboration.

Given the fixed tariffs from customs authorities, they profit by running the operations at a minimal cost (shortened duration time).

However, there is always a risk of loss under dynamic operational situations, such as peaks and troughs in operational volume and changing inspection ratios as instructed by customs authorities. The presented results in previous sections were also based on a customs centre in China, so the results should be verified through the various circumstances that other customs centres might have with their shippers and customs regulations.

To conduct the sensitivity test for the benefit of TSS1 over SRS, the duration of shipments using the TSS1 method was compared to that of SRS under stressful environments in terms of handling volume and sampling rates. The stress scenarios were designed to reflect real-world customs operations in cross-border e-commerce in two ways: increasing the number of box quantities in populations ($1.0 \times - 2.0 \times$) and using various inspection sampling

rates (0.62–4.29%). The first treatment reflects the ongoing development of cross-border e-commerce, which shows a steep growth rate due to dynamic market expansion across continents. The second treatment is relevant to customs authorities' changed policies imposed on international shipments. For example, the Chinese customs authority has a differentiated sampling ratio for physical inspections based on credibility grades for importing companies (0.62% for the highest grade to 4.29% for the lowest grade). The results from the 21 scenarios (3 types of volume $\times$ 7 types of sampling rates) over 70 days of operations span are summarised in Table 7.

Improvements in efficiency by applying TSS1 instead of SRS were consistently demonstrated in all scenarios. Moreover, the improvement increased with the smaller sampling rates (m/M) since the required times for disassembling the 1st stage sampled pallets are saved in the smaller sampling rates. The benefit of TSS1 also increased as the handling volume grew. Thus,

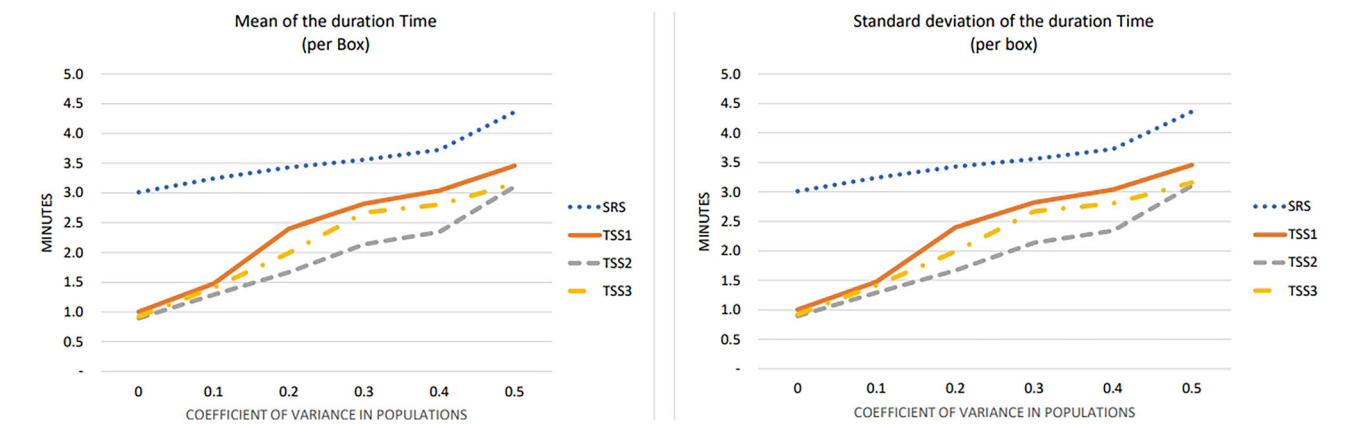


Fig. 4 The plot presents the means and standard deviations of the promptness performance among the four sampling strategies. Source: Authors' own elaboration.

Table 7 The resilience performance of the sampling method.						
Duration time per shipment (minutes)						
Designed situations		SRS		TSS1		Efficiency improvement ^c ($\mu_1 - \mu_2$) / (μ_1)
Handling volume (box qty)	Sampling rate ^a (m/M)	Mean (μ_1)	Standard deviation (σ_1)	Mean (μ_2)	Standard deviation (σ_2)	
x 1.0 Box quantity in population	0.62%	13.4	1.4	1.9	0.2	85.9%***
	1.79%	14.7	1.1	3.3	0.3	77.6%***
	2.00%	15.1	0.6	3.5	0.3	76.6%***
	2.63%	16.8	1.6	9.2	1.3	45.5%***
	3.00%	20.4	3.0	13.4	1.3	34.3%***
	4.00%	33.8	1.9	26.7	3.3	21.0%***
x 1.5 Box quantity in population	4.29% ^b	42.1	1.2	33.2	2.8	21.2%***
	0.62%	16.8	1.0	1.5	0.1	90.9%***
	1.79%	17.8	0.6	2.5	0.4	85.8%***
	2.00%	18.3	0.8	3.0	0.3	83.7%***
	2.63%	21.6	1.6	10.9	0.9	49.5%***
	3.00%	27.6	0.9	19.2	0.5	30.2%***
x 2.0 Box quantity in population	4.00%	66.7	12.1	41.7	4.6	37.5%***
	4.29% ^b	89.1	8.4	56.2	11.2	36.9%***
	0.62%	26.1	6.1	1.3	0.1	95.1%***
	1.79%	35.0	9.9	2.2	0.1	93.8%***
	2.00%	41.4	8.4	2.3	0.1	94.5%***
	2.63%	45.0	7.2	19.2	2.9	57.3%***
	3.00%	73.8	11.5	54.6	14.6	26.1%***
	4.00%	219.4	21.0	173.3	19.6	21.0%***
	4.29% ^b	233.3	26.2	184.5	13.8	20.9%***

^aThe sampling rate used for the analysis of the quality and efficiency in this study.

^bThe sampling rate used in the previous analysis (4.29%) was differentiated in the simulation model, which indicated enhanced efficiency.

^cff

*** for $p < 0.01$, ** for $p < 0.05$, * for $p < 0.10$, ns for $p > 0.10$ (ns: non-significant by two-tails), Source: Authors' own elaboration.

warehouse LSPs over various shippers and regulations can safely handle efficient operations by implementing TSS1 sampling methods for physical inspections.

Discussion

Academic significance. Previous research on logistics efficiency in international trade has highlighted the impact of advanced technologies on improving accuracy and reducing customs clearance times (Lebid et al., 2021; Shikur, 2022). Moreover, the use of data-driven sampling techniques in trade facilitation has been explored in various countries, including the EU, South Korea, and Vietnam (Nguyen et al., 2021; Vovchenko et al., 2022).

However, while these studies focus on general trade logistics efficiency, they do not specifically address the customs clearance bottlenecks associated with cross-border e-commerce. Unlike traditional logistics research, our study uniquely applies two-stage sampling methods to improve the efficiency of customs clearance in high-volume e-commerce environments, where unpredictable shipment volumes pose challenges that traditional methods fail to address. Previous research predominantly examines customs risk management (Fang and Wang, 2021) and automation (Pesquera, 2024), but little attention has been given to the direct impact of optimised sampling strategies on reducing inspection delays.

In multilevel populations, cluster size is considered informative when the outcome variable of interest is related to cluster size.

Many studies have demonstrated that TSS1 outperforms TSS2 and TSS3 when the cluster size is informative (Innocenti et al., 2021). The findings of this study align with and extend the existing research by demonstrating how TSS1 can enhance the efficiency of customs clearance in high-volume e-commerce contexts. By applying simulation models with real-world operational parameters, this study provides empirical validation for theoretical frameworks previously discussed in the literature. The scant literature on sampling theory underscores the significance of population information in choosing units because of its improved efficiency under real-life operations.

In this study, we efficiently estimated the noncompliance rate using information on the number of boxes in the pallet. We successfully applied this theory to the field of logistics, which has gained favourable theoretical support for addressing the challenges of timelines and effectiveness of customs clearance. Thus, customs clearance centres can construct cost-saving sampling procedures without jeopardising border control security. Additionally, the research offers a scalable approach that can be adapted to different customs environments worldwide, particularly in emerging economies where trade volume is rapidly increasing.

Future research can explore integrating artificial intelligence (AI) and machine learning models to optimise the selection criteria within TSS1 further. Studies on AI-driven sampling for customs inspections in high-risk shipments (Pesquera, 2024) could provide valuable insights into enhancing risk assessment capabilities. Moreover, the application of blockchain technology for tracking and verifying sampled shipments (Yan, 2024) could significantly reduce fraud and improve transparency in international trade.

Practical significance. This study provides broad insights into customs clearance operations from the perspectives of the three primary stakeholders: customs authorities, online shoppers, and warehouse logistics service providers (LSPs). Unlike previous studies that often concentrated solely on a single stakeholder, this research offers a multi-objective optimisation approach to identify an optimal sampling strategy—TSS1—that simultaneously addresses stakeholder priorities in accuracy, promptness, and resilience.

Customs authorities prioritise accuracy in inspections to mitigate risks associated with imported goods. TSS1 enhances inspection accuracy by proportionally sampling pallets based on size, improving the detection of prohibited or counterfeit items, as demonstrated by pilot projects in Shanghai and Shenzhen (Jing et al., 2024). Further, the increase in individual packages introduces complexities related to data interoperability, specialised expertise, and regulatory compliance. To address these challenges, customs authorities can implement technological integration, minimising operational disruptions. Employing AI systems that dynamically adjust sampling rates based on pre-advised information (such as pallet size, LSP credibility, shipper and country risk profiles) can streamline regulatory processes and enhance compliance efficiency. Blockchain integration for transparency can be progressively integrated, supported by collaborations between technology providers and regulatory bodies to address interoperability and compliance issues (Singapore Customs, 2017). Additionally, blockchain platforms like Maersk and IBM's TradeLens, implemented by customs authorities globally, have enhanced transparency, providing secure, verifiable shipment tracking (Rogers, 2023).

Online shoppers value prompt delivery (Timeliness) and perceive delays at customs for cross-border e-commerce as significant negatives influencing satisfaction, loyalty, and

repurchase intention (Do et al., 2023). According to a qualitative survey on customs clearance in e-commerce (Zwaan, 2024), delays in customs clearance often lead to customer frustration in the end, even though logistics integrators are not responsible for the delays. So e-commerce platforms such as AliExpress and Alibaba have significantly enhanced customer satisfaction and reduced complaints through streamlined logistics and customs clearance processes facilitated by structured sampling methods (Tudor Ackroyd, 2023). Similarly, Temu's strategic investment in logistics improvements, including localised warehouses and efficient customs procedures, has noticeably improved delivery times and customer retention rates (Fobes, 2023).

Warehouse LSPs prioritise operational efficiency to handle fluctuating shipment volumes and evolving customs policies. In Fig. 4, it is shown that TSS1 indicates far lower duration time than SRS under the various types of multi-level sample structures (i.e. coefficient of variance to the number of boxes per pallet). From the lower duration time in the customs clearance centre, the warehouse LSP can process more shipments within the operation hours that involve costly resources, including labour and utility costs. After all, it leads to the customs efficiency of operational bodies in the Air cargo industry, such as airlines, forwarders, integrators and airports (Van Asch et al., 2020). TSS1 improves efficiency by significantly reducing handling costs and time through selective pallet disassembly strategies, as exemplified by DHL's Madrid air freight hub (Interlake Mecalux, 2025). However, initial financial investments, logistical complexities, and transitional disruptions during infrastructure upgrades pose substantial challenges, as seen in Guangzhou and Ningbo (Yu, 2022). Solutions include phased investments coupled with rigorous project management to minimise disruptions during transitions. Partnering with technology providers can facilitate the efficient deployment of advanced sorting and scanning technologies. Comprehensive and ongoing training programmes, like those successfully implemented by the Korean Customs Service, ensure personnel adaptability and proficiency in advanced sampling methods (Park, 2022).

Overall, these real-world examples underline the substantial practical implications of adopting TSS1. Successfully implemented pilot projects across various regions demonstrate its potential for global scalability, enhancing the effectiveness, speed, and reliability of customs clearance operations in cross-border e-commerce contexts.

Conclusion. This study aimed to improve the CBEC customs clearance bottleneck by adopting a TSS method. We demonstrated the advantage of the TSS method in reducing the labour-intensive content-checking process by considering all stakeholders' viewpoints (Giuffrida et al., 2021). This study benchmarks the performance of several sampling methods by running a simulation model for customs centres with various operational parameters. The first sampling method, TSS1, sampled pallets with a probability proportional to the pallet size and subsequently sampled a fixed number of boxes from each sampled pallet. The second sampling method, TSS2, sampled pallets with equal probability and thereafter sampled a flexible number of boxes based on the same ratio across different pallet sizes. The last one, TSS3, sampled pallets with equal probability and subsequently sampled a fixed number of boxes from each pallet. Compared with SRS, which excludes cluster membership by disassembling all pallets, TSS1, TSS2, and TSS3 were measured in terms of the required performance, accuracy, promptness, and resilience.

TSS1 consistently provided the most accurate detection boxes, exhibiting a marginally longer duration than TSS2 and TSS3. This was based on its proportionate pallet selection to the pallet size in

the first stage. However, TSS1 was found to be superior to SRS in terms of promptness. Finally, the comparative benefit of TSS1 was assessed under rigorous scenarios that included inflation of the population size and different sampling rate policies. TSS1 showed a resilient advantage over SRS in terms of average shipment processing time. Thus, the proposed sampling method, TSS1, satisfied the interests of all three stakeholders.

Scope of future research and limitations. For future studies, we recommend implementing an intelligent method of utilising population data extracted from big data technologies (Guan, 2021; Li, 2019; Zhang et al., 2021). This should extend beyond the number of packages on the pallet to improve the efficiency of customs clearance. Future studies should integrate more modern scientific and technological means to jointly reduce customs risks and reduce the duration of goods in customs for global trade. Furthermore, an integrated view of the differences in customs clearance time across countries is still unknown. For example, there is a sizable difference in the reported customs clearance times per parcel: Brazil (2 days), the US and India (24 h), China (2 h), Australia and Germany (1 h), Korea and Japan (15 min), and Singapore (10 min) (Bobirovich, 2024). Future research should provide an integrated view of custom operations, including infrastructure and risk assessment policies, to examine the differences in countries because their consequences are significant in the supply chain.

A limitation of the current study is that it assumes that the goods in the same batch of customs clearance must be distributed by the same domestic logistics company, which simplifies the situation, but can also be informative. The assumption is that all packages on the same tray or batch of goods are from the same express service company in the country of departure. Therefore, this study further explores how shippers with distinctive credibility should handle the customs clearance method.

Therefore, it is significant for countries to draft their internationalisation strategies to handle the customs clearance process, given the opportunities in the CBEC. Efficient customs clearance systems will be crucial, given that the rapid growth of express delivery networks is fuelling international online shopping. Shortly thereafter, the issue of the customs clearance centre bottleneck will become more visible in supply chains. Therefore, this study addresses the last piece of the puzzle for the seamless operation of cross-border e-commerce.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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References

- Addo A (2022) Information technology and public administration modernization in a developing country: pursuing paperless clearance at Ghana customs. *Inf Syst J* 32:819–855
- Van Asch T, Dewulf W, Kupfer F, Cárdenas I, van de Voorde E (2020) Cross-border e-commerce logistics—Strategic success factors for airports. *Res Transp Econ* 79:100761
- Ayesu EK, Sakyi D, Baidoo ST (2024) The effects of seaport efficiency on trade performance in Africa. *Marit Policy Manag* 51:420–441
- Baashirah R, Elleithy K (2019) Automation of the baggage check-in process using RFID system in airports. In: *Proceedings of the IEEE long island systems, applications and technology conference (LISAT)*. IEEE, pp 1–4
- Beverelli C, Ticku R (2022) Reducing tariff evasion: the role of trade facilitation. *J Comp Econ* 50:534–554
- Bobirovich SM (2024) Facilitation of trade and modernization of customs procedures. *Int Multidiscip J Res Dev* 11
- Bowman LJ (2022) Statista. *J Bus Financ Librariansh* 27:304–309
- Caballini C, Benzi M (2023) Fast corridors: innovative customs processes and technology to increase supply chain competitiveness. The case of IKEA Italy. *Transp Res Interdiscip Perspect* 21:100909
- Çelebi Ü (2022) The impact of trade costs upon gross domestic product: the customs efficiency index as a mediator. *World Cust J* 16:23–35
- Chang Z, Yang D, Wan Y, Han T (2019) Analysis on the features of Chinese dry ports: ownership, customs service, rail service and regional competition. *Transp Policy* 82:107–116
- Chen T, Qiu Y, Wang B, Yang J (2022) Analysis of effects on the dual circulation promotion policy for cross-border e-commerce B2B export trade based on system dynamics during COVID-19. *Systems* 10:13
- Danladi C, Tuck S, Tziogkidis P, Tang L, Okorie C (2024) Efficiency analysis and benchmarking of container ports operating in lower-middle-income countries: a DEA approach. *J Shipp Trade* 9:7
- Deloitte (2019) China's demand for imported consumer goods remains strong, bolstered by digital upgrades in cross border e-commerce. <https://www2.deloitte.com/cn/en/pages/about-deloitte/articles/pr-china-consumer-import-consumer-market-research-report.html> (accessed 27 Aug 2022)
- Desiderio D (2019) Data analysis techniques for enhancing the performance of customs. *World Cust J* 13:17–22
- Ding T, Zhu W, Zhao M (2022) Does cross-border logistics performance contribute to export competitiveness? evidence from china based on the iceberg transport cost model. *Sustainability* 15:490
- Do QH, Kim TY, Wang X (2023) Effects of logistics service quality and price fairness on customer repurchase intention: the moderating role of cross-border e-commerce experiences. *J Retail Consum Serv* 70. <https://doi.org/10.1016/j.jretconser.2022.103165>
- Faccia A, Mosteanu NR (2019) Tax evasion, information systems and blockchain. *J Inf Syst Oper Manag* 13:65–74
- Fang Z, Wang Q (2021) Cross-border e-commerce supply chain risk evaluation with FUZZY-ISM model. *Security and Communication Networks* 2021
- Fobes (2023) How Temu is winning customers with bargains and fast delivery. <https://www.forbes.com/sites/zengernews/2023/04/27/how-temu-is-winning-customers-with-bargains-and-fast-delivery/> Accessed 29 Mar 2025
- Gao B, Garrido A, Walker A (2023) Connected freight transport advances and benefits. *Transp Res Procedia* 72:3198–3204
- Gao Q, Kuang Z (2023) Can robotic process automation technology enable risk data analysis for customs' post-clearance audit: a china customs case study. *World Cust J* 17:93–104
- Giuffrida M, Mangiaracina R, Perego A, Tumino A (2020) Cross-border B2C e-commerce to China: an evaluation of different logistics solutions under uncertainty. *Int J Phys Distrib Logist Manag* 50:355–378
- Giuffrida M, Jiang H, Mangiaracina R (2021) Investigating the relationships between uncertainty types and risk management strategies in cross-border e-commerce logistics. *Int J Logist Manag*
- Guan S (2021) Smart E-commerce logistics construction model based on big data analytics. *J Intell Fuzzy Syst* 40:3015–3023
- Guercini S, Ranfagni S, Runfola A (2020) E-commerce internationalization for top luxury fashion brands: some emerging strategic issues. *J Manag Dev* 39(4):423–436
- Hiraide T, Hanaoka S, Matsuda T (2022) The efficiency of document and border procedures for international trade. *Sustainability* 14:8913
- Hu R, Lau Y-Y, Wang R (2023) Evaluation of customs supervision competitiveness using principal component analysis. *Sustainability* 15:1833
- Hua T (2022) Development of the system of customs experts—the example of China Customs. *World Customs J* 16
- Ibrahim RL, Ajide KB (2022) Trade facilitation and environmental quality: empirical evidence from some selected African countries. *Environ Dev Sustain* 24:1282–1312
- Innocenti F, Candel MJJM, Tan FES, van Breukelen GJP (2021) Optimal two-stage sampling for mean estimation in multilevel populations when cluster size is informative. *Stat Methods Med Res* 30(2):357–375
- Interlake Mecalux (2025) Pallet racks and mezzanine floor for DHL in Spain—interlake Mecalux. Interlake Mecalux. <https://www.interlakemecalux.com/case-studies/-logistics-center-for-dhl-in-spain> (accessed 29 Mar 2025)
- Jing W, Zheng Y, Shen X (2024) Does the establishment of Pilot Free Trade Zones promote international expansion of enterprises? Quasi-natural experimental evidence from China. *PLoS One* 19. <https://doi.org/10.1371/journal.pone.0308477>
- Konstantinus A, Woxenius J (2022) Case study: coastal shipping in sub-Saharan Africa. *Case Stud Transp Policy* 10:2064–2074

- Kornher L, Sakyi D, Tannor LL (2024) "When you need it quick, let us ship it right": On the importance of port efficiency and service quality to comply with food trade standards in Ghana. *Rev World Econ* 1–25
- Lebid V, Anufriyeva T, Savenko H, Skrypnik V (2021) Study of efficiency of simplification of customs formalities on the digitalization basis. *Technol Audit Prod Reserves* 1:57
- Levy PS, Lemeshow S (2013) Sampling of populations: methods and applications. John Wiley & Sons
- Li W (2019) Time barrier to trade: data on 190 economies' export and import time, 2005–2018. *Data Brief* 22:508–515
- Liang Y, Guo L, Li J, Zhang S, Fei X (2021) The impact of trade facilitation on cross-border E-Commerce transactions: analysis based on the marine and land cross-border logistical practices between China and countries along the "belt and road. *Water* 13:3567
- Liu A, Osewe M, Shi Y, Zhen X, Wu Y (2021) Cross-border E-commerce development and challenges in china: a systematic literature review. *J Theor Appl Electron Commer Res* 17:69–88
- Lohr SL (2021) Sampling: design and analysis. Chapman and Hall/CRC
- de Melo J, Sorgho Z, Wagner L (2024) Reducing wait times at customs to boost trade: how implementing the trade facilitation agreement can expand trade among AfCFTA countries? *J Afr Econ* ejae008
- Nguyen HT, Grant DB, Bovis C, Nguyen TT Le, Mac YTH (2021) Factors affecting efficiency of electronic customs and firm performance in Vietnam. *J Asian Financ Econ Bus* 8:151–164
- Niu B, Wang J, Lee CKM, Chen L (2019) Product+ logistics" bundling sale and co-delivery in cross-border e-commerce. *Electron Commer Res* 19:915–941
- Omosa AM (2022) Effect of systems automation on customs revenue performance in Kenya. *Afr Tax Cust Rev* 5:38–p60
- Park H (2022) KCS takes its first steps into R&D. <https://mag.wcoomd.org/magazine/98-issue-2-2022/kcs-rd/> (accessed 29 Mar 2025)
- Pesquera MA (2024) Automation in logistics port and freight transport with blockchain technology. *Transp Res Procedia* 78:394–401
- Rbehat AM, Marafi HB (2024) The role of customs process in facilitating international trade. *Saudi J Bus Manag Stud* 9:7–14
- Rogers C (2023) How maersk used blockchain to revolutionize the logistics industry. <https://medium.com/geekculture/how-maersk-used-blockchain-to-revolutionize-the-logistics-industry-case-study> (accessed 29 Mar 2025)
- Sanjahaya Jahir S, Lubis TM, Lubis AF (2024) Analysis of the effectiveness of customs services in the perspective of law in Indonesia. *West Sci Law Hum Rights* 2:211–217
- Shikur ZH (2022) The role of logistics performance in international trade: a developing country perspective. *World Rev Intermodal Transp Res* 11:53–69
- Shpak N, Melnyk O, Adamiv M, Sroka W (2020) Modern trends of customs administrations formation: best European practices and a unified structure. *NISPAcee J Public Adm Policy* 13:189–211
- Singapore Customs (2017) Data analysis in risk management: Singapore Customs' perspective. <https://mag.wcoomd.org/magazine/wco-news-82/data-analysis-in-risk-management-singapore-customs-perspective/> (accessed 29 Mar 2025)
- Snijders TAB, Bosker R (2011) Multilevel analysis : an introduction to basic and advanced multilevel modeling. London:Sage, 368
- Song B, Yan W, Zhang T (2019) Cross-border e-commerce commodity risk assessment using text mining and fuzzy rule-based reasoning. *Adv Eng Inform* 40:69–80
- Taconeli CA, Cabral AdaS (2019) New two-stage sampling designs based on neoteric ranked set sampling. *J Stat Comput Simul* 89:232–248
- Tadesse MD, Kine HZ, Gebresenbet G, Tavasszy L, Ljungberg D (2022) Key-logistics performance indicators in low-income countries: the case of the import–export chain in ethiopia. *Sustainability* 14(19):12204
- Tudor Ackroyd A (2023) Cainiao to roll out 5-day delivery service globally <https://www.alizila.com/cainiao-aliexpress-launch-5-day-delivery-service-express-brand-smart-logistics-china/> (accessed 29 Mar 2025)
- Vovchenko N, Ivanova O, Kostoglodova E, Khapilin S, Sapegina K (2022) Improving the customs regulation framework in the eurasian economic union in the context of sustainable economic development. *Sustainability* 14:755
- Wang X, Xie J, Fan Z-P (2021) B2C cross-border E-commerce logistics mode selection considering product returns. *Int J Prod Res* 59:3841–3860
- Widdowson D (2020) Managing customs risk and compliance: an integrated approach. *World Cust J* 14:63–80
- Willersdorf S, Hazan J, Ricci G, Prénaud A, Bianchi F, Seara J, Yang V (2020) A new era and a new look for luxury. BCG. Luettavissa: <https://www.bcg.com/publications/2020/newera-and-new-look-for-luxury>. Luettu 12, 2022
- Xinhua (2022) China's cross-border e-commerce gains growth momentum, bolsters consumption. https://english.www.gov.cn/news/topnews/202204/26/content_WS62675588c6d02e5335329edd.html (accessed 27 Aug 2022)
- Yan Y (2024) Optimization of import and export of aquatic products in zhanjiang city-platform construction based on blockchain perspective. *Appl Math Nonlinear Sci* 9. <https://doi.org/10.2478/amns-2024-1535>
- Yang Q (2022) Design and implementation of RFID-based logistics clearance information platform, in: The international conference on cyber security intelligence and analytics. Springer, pp 585–592
- Yu H (2022) Enterprises in E. China's Ningbo smooth foreign trade supply chain with overseas warehouses. <https://en.imsilkroad.com/p/327986.html> (accessed 29 Mar 2025)
- Zhang X, Xu D, Xiao L (2021) Intelligent perception system of big data decision in cross-border e-commerce based on data fusion. *J Sens* 2021
- Zwaan S (2024) From click to clearance: the effect of e-commerce order processing on customs clearance at airports. Erasmus University Rotterdam, Rotterdam

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The authors declare no competing interests.

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This was not obtained as the research does not involve any human participants or their data.

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