AI-Driven Construction of an Intelligent Customs System in the Guangdong-Hong Kong-Macao Logistics Park: Innovations in Bonded Ledger Management and Cross-Border Data Integration

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Abstract. Targeting the "three complexities" pain points of the Guangdong-Hong Kong-Macao Logistics Park—diversified cross-border logistics supervision, varied business formats, and fragmented systems—and in response to the mandatory requirements of the General Administration of Customs Announcement No. 174 of 2024 on dynamic balancing of bonded account books and fully electronic management, this paper constructs an AI-driven Intelligent Customs System (ICS). The system deeply integrates OCR, natural language processing, Transformer encoding mapping, and a dynamic account book verification engine. Based on a cloud-native microservice architecture, it realizes automation of cross-border declarations and data synchronization between the Warehouse Management System (WMS) and customs account books, ultimately achieving secure dual-declaration interaction. This study selects a dataset consisting of 100,000 trade records and 50,000 release verification documents from 52 enterprises in the park between January 2024 and March 2025, with the dataset split into 80% training set, 10% validation set, and 10% test set. Traditional manual verification and general OCR are used as baseline benchmarks. Practical verification shows that the system reduces the account book discrepancy rate from 18% to 0.3%, achieves a 95% accuracy rate in HS code conversion, cuts document rejection rate by 82%, improves release verification document processing efficiency by 50%, and lowers labor costs by 60%. These results significantly enhance cross-border logistics processing efficiency and customs supervision compliance, providing a replicable practical paradigm for the construction of smart customs in the Guangdong-Hong Kong-Macao Greater Bay Area.

Keywords: Intelligent Customs System; Artificial Intelligence (AI); Guangdong-Hong Kong-Macao Logistics Park; Microservices Architecture; Cross-border Data Integration; Bonded Ledger Management

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1 Introduction

Driven by the integrated development of the Guangdong-Hong Kong-Macao Greater Bay Area, cross-border bonded logistics has expanded rapidly. The Guangdong-Hong Kong-Macao Logistics Park next to the Hong Kong-Zhuhai-Macao Bridge acts as a key cross-border supply chain hub, covering bonded warehousing, processing trade and cross-border e-commerce.

However, its daily operations suffer from three major drawbacks: inefficient manual ledger reconciliation with high imbalance rates, manual HS code conversion causing frequent document rejection, and isolated WMS/ERP/customs systems triggering persistent inventory data mismatches. Meanwhile, General Administration of Customs Announcement No.174 of 2024 enforces dynamic ledger balance, full electronic filing and regular verification, making traditional semi-manual modes obsolete.

This study constructs an AI-powered Intelligent Customs System (ICS) based on cloud-native microservices. It integrates multimodal OCR, graph neural network extraction and Transformer HS code mapping, alongside a dynamic bonded ledger verification engine to achieve automated cross-border declaration and real-time warehouse-customs data synchronization.

Validated with real business data from 52 local enterprises, the system remarkably cuts ledger errors, document rejection rates and labor expenditure while boosting clearance efficiency. Its technical framework offers replicable experience for smart customs construction in other Bay Area bonded zones.

1.1 Research Background

The Guangdong-Hong Kong-Macao Logistics Park is situated at the first exit of the Zhuhai Link of the Hong Kong-Zhuhai-Macao Bridge in Xiangzhou District, Zhuhai City. It is located merely 15 kilometers from the bridge port, offering one-hour access to Hong Kong Airport and a 30-minute drive to Macao Airport. As the nation's first logistics hub directly connected to both Hong Kong and Macao first-tier ports, the park has a total floor area of 143,100 square meters. It is being developed in three phases and integrates bonded warehouses, export supervision warehouses, a cold chain center, and a cross-border e-commerce industrial park, collectively forming a global supply chain service center. Leveraging the "golden channel" advantage of the Hong Kong-Zhuhai-Macao Bridge, the park has reduced cross-border logistics lead times by 67%. It handles over 5,000 tons of cargo daily and has attracted more than 20 leading enterprises, including Shein, Pinduoduo, Watsons, and Gree Electric Appliances. As a core hub connecting Hong Kong, Macao, and global supply chains, the Guangdong-Hong Kong-Macao Logistics Park exhibits a typical "threefold multiplicity" in its bonded operations. At the regulatory level, it involves multiple oversight bodies, including mainland customs, Hong Kong customs, and the Macao Municipal Affairs Bureau. In terms of business models, it encompasses various forms such as bonded warehousing, processing trade, and cross-border e-commerce. Regarding information systems, there is a current state of fragmentation among Warehouse Management Systems (WMS), Enterprise Resource Planning (ERP) platforms, and customs decla-

ration systems. Taking the bonded mineral water business of QCS Company, a key enterprise in the park, as an example, its supply chain closed loop—characterized by "Hong Kong concentrate entering the zone, processing in Guangzhou, and finished products returning to the zone for export"—faces three prominent bottlenecks.[1]

Firstly, the traditional manual verification method suffers from low efficiency and a high error rate.[2]

The account book imbalance rate of QCS Company reached 18% in 2024, significantly exceeding the customs early warning threshold of 5%. In the auxiliary materials verification process, such as requiring 4.17 pallets for every 100 cases of bottled water, manual calculation errors resulted in over 30 supplementary tax declarations annually on average, severely impacting the company's operational efficiency.

Secondly, differences in declaration standards between Guangdong and Hong Kong impose substantial operational costs. For declarations in the Hong Kong segment, the mainland's 10-digit HS code must be manually converted to Hong Kong's 8-digit code, with a single-document conversion error rate of 12%. [3]The Hong Kong warehouse of QCS Company experiences more than 200 document rejections monthly due to commodity classification discrepancies, with an average processing time of 4.5 hours per document, greatly constraining border clearance efficiency.

Thirdly, fragmented systems lead to regulatory risks. The WMS system in the logistics park lacked real-time synchronization with the customs verification ledger. In the first quarter of 2024, there were 17 instances of discrepancies where the system showed inventory while the customs ledger had already been cleared. These anomalies repeatedly triggered customs alerts, thereby increasing the company's compliance risks.[4]

Against this backdrop, Announcement No. 174 of 2024 issued by the General Administration of Customs introduced three mandatory requirements for the management of bonded logistics ledgers. First, an annual verification system was implemented, requiring enterprises to complete their reporting within 60 days. Second, a dynamic balancing mechanism was established, mandating that the discrepancy rate between the ledger inventory and the customs ledger should not exceed 5%. Third, a full transition to electronic verification was mandated, eliminating the circulation of paper documents.[5] These new regulations have imposed more stringent demands on the ledger management practices within the Guangdong-Hong Kong-Macao Logistics Park. To address these challenges, this study proposes three key technological breakthroughs: establishing a dynamic verification engine to enable real-time data linkage among "verification lists, inventory, and verification processes"; developing an intelligent HS code conversion model to support second-level mapping for commodity classification between Guangdong and Hong Kong; and integrating WMS and customs system APIs to build a digital twin system covering the entire lifecycle of bonded goods.[6] These technological innovations will provide crucial support for resolving regulatory discrepancies across Guangdong, Hong Kong, and Macao, and for enhancing the efficiency of cross-border logistics.

2 Key Technology Solutions for the Smart Customs Warehousing System in the Guangdong-Hong Kong-Macao Logistics Park

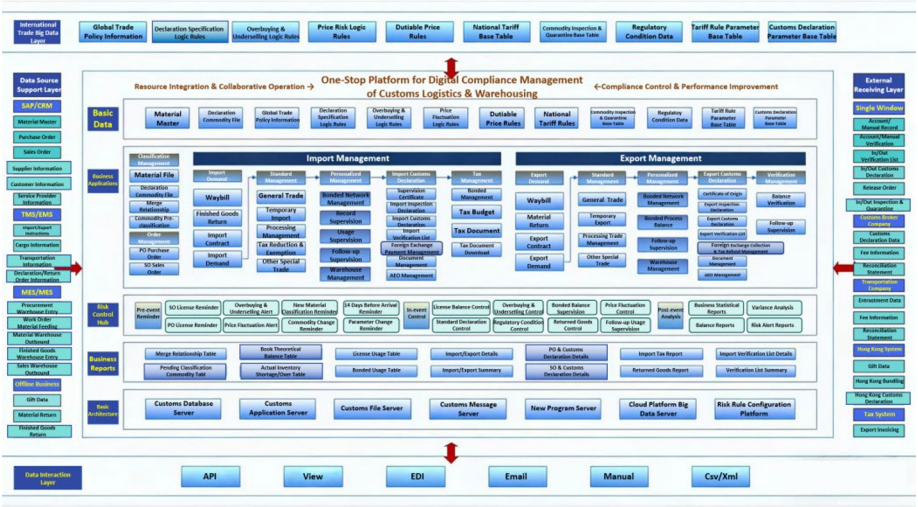

Fig. 1. The Smart Customs and Warehousing System of the Guangdong-Hong Kong-Macao Logistics Park

The Intelligent Customs System for the Guangdong-Hong Kong-Macao Logistics Park adopts a cloud-native microservice layered architecture, consisting of a big data layer, an external interface layer, a business center platform, and a basic data layer.(Figure 1) It connects external systems including customs, taxation, and logistics, creating a new cross-border clearance model featuring "one-time entry, shared data across three regions", which reduces manual links by 70%.Built on Spring Boot/Cloud, the system utilizes Docker containerization and Kubernetes (K8s) orchestration, supporting high concurrency and high availability. The smart customs logistics warehousing digital compliance one-stop platform at the Guangdong-Hong Kong-Macao Logistics Park adopts a layered architecture design, establishing an intelligent management system that covers the entire process of cross-border trade.[7]The system is built around a big data layer that integrates international trade data, global supply chain information, and enterprise operational data. The platform particularly enhances customs-warehouse coordination. By enabling real-time linkage between the Warehouse Management System (WMS) and customs verification lists, it automates the entire process from declaration and release to verification. A foundational data layer establishes standardized databases for commodities, enterprise information, and declaration elements, providing the necessary data support for intelligent classification and compliance validation.[8]Through its modular design, the platform accommodates the differentiated regulatory requirements of Guangdong, Hong Kong, and Macao while establishing a novel cross-border customs clearance model characterized by "single data entry and

tri-regional data sharing." This approach reduces traditional manual processing steps by 70 percent and significantly enhances the operational efficiency of the logistics park.[9]

2.1 Dynamic Verification Technology for Bonded Ledgers

The platform employs an intelligent verification engine to manage the entire lifecycle of bonded ledgers, with its core technology lying in deep integration with the enterprise's Warehouse Management System (WMS). The system is deeply integrated with enterprises' Warehouse Management System to obtain real-time inventory and in-transit inventory data, establishing a three-dimensional verification model of "Declaration Form- Actual Inventory-Theoretical Inventory".[10]It automatically triggers a four-level alert and freezes documents in response to shortages of auxiliary materials. To adapt to the annual customs verification, an innovative "progressive migration" algorithm is designed. During the 6-month transition period, the "exit-only" policy is implemented for old account books. Through segment isolation of declaration numbers, the migration error of concentrated solutions (HS21069090) from QCS Company is controlled within 0.5%. The loss calibration module leverages big data analytics from production processes. When material input deviations exceed predefined thresholds, the system automatically matches historical process parameters from its database to recommend optimization solutions. This approach successfully reduced the loss rate for bottled mineral water from 2.1% to 1.8%.

2.2 End-to-End Automation of the Verification List

The system employs multimodal AI technology to redesign the document processing workflow. An enhanced OCR engine identifies complex layouts in QCS company invoices, such as multi-page tables and handwritten annotations. This is combined with a Dynamic Graph Convolutional Network (DGCNN) algorithm to parse topological relationships within unstructured data. Consequently, the conversion of packing list information into a structured verification list is completed within 30 seconds. A customs-warehouse collaboration mechanism establishes a bidirectional data channel. Once a shipping wave is generated by the WMS, it automatically triggers the submission of the verification list. Customs clearance notifications are then written back to the WMS inventory ledger in real-time via an MQ message queue, creating a millisecond-level closed loop for "command, declaration, and feedback" (Figure 2). For goods designated for destruction (code 0200), the system innovatively employs a "blockchain + video fingerprint" technology. This approach involves uploading the hash values of key frames from surveillance footage to the blockchain for notarization, thereby fulfilling customs' requirement for a three-year traceability of the entire destruction process.

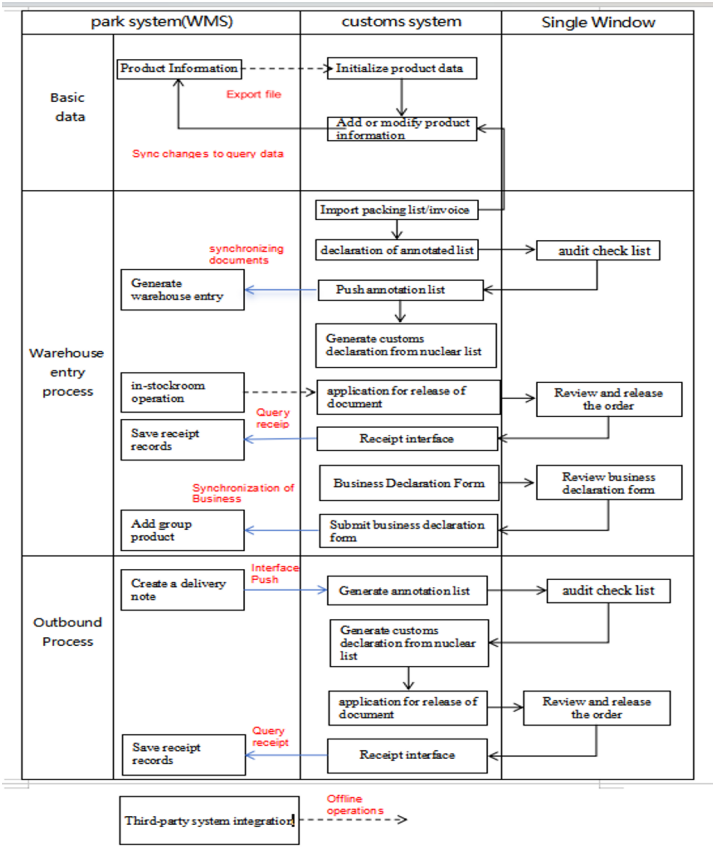

Fig. 2. Flowchart of the Customs-Warehouse Collaboration Mechanism

2.3 The Guangdong-Hong Kong "One Declaration, Two Reports" System

The platform has achieved a breakthrough by constructing a cross-jurisdictional rule conversion engine. This engine features an HS code mapping model based on the Transformer architecture, which utilizes an attention mechanism to learn the feature vectors of Mainland China's 10-digit codes and Hong Kong's 8-digit codes, achieving a 95% accuracy rate in commodity classification (Figure 3). The declaration coordination system employs a three-tier processing architecture comprising data cleansing, format conversion, and encrypted transmission. Data from Guangdong's Single Window is encrypted using the SM4 national cryptographic algorithm and then transmitted via a dedicated channel to Hong Kong's ROCARS system. This process has enabled QCS Company to reduce the number of fields requiring manual input for Hong Kong declarations from nine to zero. The system's built-in intelligent rule repository contains over 3,000 dynamic classification rules.

ORIGINAL ENGLISH TRADE NAME FROM DOCUMENTS → MACHINE TRANSLATION → TEXT SIMILARITY MATCHING → RETRIEVE CORRESPONDING HONG KONG HS CODE

ENGLISH COMMODITY NAME	CHINESE NAME AFTER MACHINE TRANSLATION	NAME WITH THE HIGHEST SIMILARITY IN HISTORICAL DATABASE	CORRESPONDING HK CUSTOMS CODE OF THE HISTORICAL DATABASE
PET UNDERWEAR	PET UNDERWEAR	PET UNDERWEAR	39269090
RESIN CRAFT	RESIN TECHNOLOGY	RESIN TECHNOLOGY	39264000
REPLACEMENT EARPADS	EARPLUG REPLACEMENT	EAR COVERS	63079090
MAC BOOK PRO PI967	MAC BOOK PRO PI967	APPLE LAPTOP	84713090
SMART WATCH	SMART WATCH	SMART WATCH	85176900
RASHGUARD	LASHA MELON		
PHONE	TELEPHONE	MOBILE PHONE	85171310
SHIFT KNOB	GEAR SHIFT KNOB	GEAR SHIFT KNOB	39269090
MINI PC PI967	MICROCOMPUTER PI967	MINI COMPUTER	84714900
FIBER FUSIONSPLICER PI967	OPTICAL FIBER FUSION SPLICER PI967	SPLICING MACHINE	84659400
SMART WATCHES	SMART WATCH	SMART WATCH	85176900
KEY BAND COCOA	BASE COCOA	SMART BAND	85249100
BARCODE SCANNER	BARCODE SCANNER	BARCODE SCANNER	84719000
SMART CARD	SMART CARD	SMART CARD	85235200
BARCODE SCANNER	BARCODE SCANNER	BARCODE SCANNER	84719000
SMART WATCH	SMART WATCH	SMART WATCH	85176900
SMART WATCH	SMART WATCH	SMART WATCH	85176900
COSMETIC BAG	COSMETIC BAG	COSMETIC BAG	42023220
AIR CONDITIONING PARTS	AIR CONDITIONING COMPONENTS	AIR CONDITIONING COMPONENTS	84159090
MANNEQUINS	MANNEQUIN	HUMAN BODY MODEL	96180005
AIR CONDITIONING PARTS	AIR CONDITIONING COMPONENTS	AIR CONDITIONING COMPONENTS	84159090
AIR CONDITIONING PARTS	AIR CONDITIONING COMPONENTS	AIR CONDITIONING COMPONENTS	84159090
DOCUMENT CAMERA	DOCUMENT CAMERA	CAMERA	85258920
SMART BRACELET	SMART BRACELET	SMART BAND	85249100

Fig. 3. Intelligent Classification of Declared Goods in Hong Kong

3 Computer Technology Implementation

The Intelligent Customs System (ICS) is fundamentally a large-scale, distributed software system built upon a modern computing technology stack. Its design and implementation are detailed across four layers: system architecture, AI & data processing core, system integration, and security.

3.1 System Architecture & Development Platform

The ICS adopts a cloud-native, microservices architecture to ensure high scalability, maintainability, and resilience in handling high-throughput cross-border declaration data. The system is decomposed into independent functional microservices deployed using Docker containers and orchestrated via Kubernetes. The backend is primarily developed using the Spring Boot and Spring Cloud frameworks, which facilitate rapid development and simplify service governance. The data persistence layer utilizes MySQL for structured relational data and Redis for caching high-frequency parameters to ensure low-latency response. [11]The front-end supports both PC and mobile operations, with a WeChat mini-program providing a streamlined interface for drivers and logistics coordinators, crucial for real-time operations like vehicle bonding/unbonding declarations at the Hong Kong-Zhuhai-Macao Bridge port.

3.2 AI & Data Processing Core

The intelligence of the ICS is powered by a multi-modal AI processing pipeline designed to automate the conversion of non-standard, unstructured trade documents into structured, compliant declaration data.[12]

3.2.1 Document Image Processing and OCR Technology.

Document Image Processing and OCR: Incoming documents undergo preprocessing . A custom-trained OCR engine is employed for text detection and recognition. For text detection, we use a Differentiable Binarization Network (DBNet), which outperforms traditional methods in detecting text in complex layouts common in invoices. For text recognition, a Convolutional Recurrent Neural Network (CRNN) model is used. This model combines CNN for visual feature extraction and RNN for sequence modeling, followed by a Connectionist Temporal Classification (CTC) layer for alignment-free transcription. This pipeline achieves a field-level recognition accuracy of 92.3% for declaration documents.[13]

3.2.2 Structured Information Extraction from Unstructured Documents.

Structured Information Extraction: Extracted text often resides in complex tables or unstructured descriptions. To parse tabular data, we implement a Dynamic Graph Convolutional Neural Network (DGCNN) . The document is modeled as a graph where text segments are nodes. DGCNN dynamically learns the relationships (edges) between nodes to classify them into key-value pairs, effectively reconstructing the table structure. For extracting specific declaration elements like brand, model, material) from free text, a Bidirectional Long Short-Term Memory network coupled with a Conditional Random Field (Bi-LSTM+CRF) model is used for Named Entity Recognition (NER).

3.2.3 Intelligent HS Code Classification Model with Transformer Architecture.

Intelligent HS Code Classification: A central challenge is harmonizing commodity classifications across jurisdictions. We developed a deep learning model based on the Transformer architecture for HS code mapping and recommendation. The model is trained on a historical database of millions of declaration forms and commodity data. It takes Chinese and English product descriptions as input, uses multi-head attention mechanisms to understand semantic context, and outputs the most probable Mainland China HS code along with its corresponding Hong Kong code. This model achieves a classification accuracy of 95%, drastically reducing manual lookup errors and Hong Kong-side rejection rates.[14]

3.3 System Integration & Data Flow

The ICS acts as a central integration hub. A dedicated API Gateway manages over 1,000 external interfaces. It handles protocol translation, rate limiting, and authentication. For asynchronous, high-volume data flows—such as synchronizing customs clearance feedback to WMS or triggering declaration processes from WMS outbound waves—we employ a distributed messaging system, Apache Kafka. This ensures reliable, decoupled, and real-time data exchange between the ICS, enterprise WMS/ERP systems, and the three customs platforms: China's International Trade "Single Window," Hong Kong's ROCARS, and Macao's "Clearance Easy.

4 Conclusion

This study, by constructing an intelligent customs system based on "AI + regulatory coordination," has successfully achieved a paradigm upgrade in customs clearance and bonded ledger management for the Guangdong-Hong Kong-Macao Logistics Park. It meets the regulatory requirements set forth in Announcement No. 174 of 2024 by the General Administration of Customs, achieving simultaneous improvement in customs clearance efficiency and compliance. Looking ahead, the technical solution proposed in this research can be further extended to Pilot Free Trade Zones like Hengqin and Qianhai. This expansion will contribute to building the Guangdong-Hong Kong-Macao Greater Bay Area into a global supply chain service center, thereby providing more efficient intelligent customs clearance support for regional economic integration.

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