AI-Driven Smart Ports and the Competitiveness of Hong Kong as a Greater Bay Area Logistics Hub: A Public-Data, Multi-Case Operational Comparison

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Abstract. Smart-port technologies, such as terminal automation, artificial intelligence (AI) and digital data-sharing, have been promoted in an effort to enhance the international competitiveness of container ports, but their application in practice to improve actual performance in the rapidly changing regional cluster has yet to be fully demonstrated. Hong Kong is a typical case: by 2024, its container throughput had fallen to a 28-year low of about 13.7 million TEU, and it had slipped out of the top ten world ports amid the rapid automation of the Greater Bay Area (GBA). Competitiveness is divided into three publicly observable attributes: operating efficiency, network connectivity and smart-port maturity. Hong Kong is then benchmarked against GBA counterparts (Shenzhen, Guangzhou) and world-class automated terminal operators (Singapore, Shanghai, Rotterdam, Qingdao) using public indices and operator and government data. Automation maturity does not correlate with operating efficiency; for example, only the semi-automated port of Hong Kong achieved the top rank in 2025 for efficiency, and many fully automated ports ranked considerably lower. AI and automation are best viewed as enabling conditions rather than the direct drivers of competitiveness, and Hong Kong's relative decline is mainly due to structural and connectivity factors.

Keywords: Smart port, port competitiveness, container terminal automation, Greater Bay Area, Hong Kong.

1. Introduction

Container ports are the links of world trade, and their efficiency will directly affect the cost of trade and the competitiveness of a country's trading. Over the past ten years, the two sides of this change have been advancing simultaneously. The first is the spread of “smart port” technologies linked to Industry 4.0, such as terminal automation, AI, the Internet of Things, digital twins, 5G and blockchain; systematic reviews now consider these to be defining features of a modern port [1]. The second is an increase in competition for throughput and hub status, especially in regional multi-port clusters where neighboring ports compete for overlapping hinterlands; the drivers of this competition, such as cost and location, connectivity and service quality, have been widely studied but not fully integrated [2].

The two are now more prominent in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), which is home to three of the busiest container ports in the world. Hong Kong, which was once the busiest port in the world, has shown a continuous structural decline: its throughput fell to about 13.7 million twenty-foot equivalent units (TEU) in 2024, a 28-year low, and the port was dropped from the top ten globally for the first time, with Shenzhen (about 33.4 million TEU) and Guangzhou [3, 4] overtaking it. Scholars believe that the reasons for this trend are structural in nature, such as manufacturing relocation, the construction of direct mainland deep-sea services and higher costs [3]. Both governments and industries have responded by promoting the development of automation and smart ports to prevent the decline.

However, the idea that AI and automation drive competitiveness is mentioned more often than it is shown. The leading port digitalisation maturity model does not connect maturity with competitiveness [5], and the most rigorous independent assessment has found that automated terminals are often no more productive than traditional ones [6]. Therefore, port competitiveness has been divided into three publicly observable dimensions: operating efficiency, network connectivity and smart-port maturity, and public data are used to benchmark Hong Kong against GBA rivals and global automated terminal leaders to determine whether automation maturity is tracking competitiveness or if structural and connectivity factors are dominating. (See Figure 1)

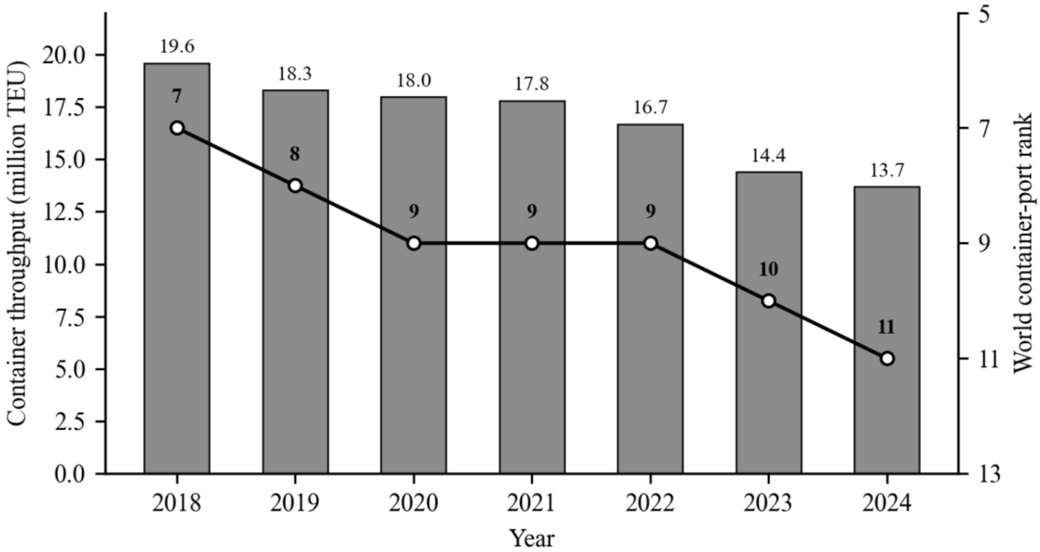

Figure 1. Hong Kong container throughput (bars, million TEU) and world container-port rank (line), 2018-2024. The World Rank is indicative and varies by source. Data: Hong Kong Maritime and Port Development Board [4].

2. Literature Review

2.1. AI and automation in port operations

The most technically mature part in the literature is the automation at the terminal "fence line". Fully automated container terminals date to the early 1990s, and systematic research has only recently picked up pace with the spread of automated guided vehicles (AGVs), automated stacking cranes, remote-controlled quay cranes and in-house terminal operating systems, as well as machine-learning methods for berth allocation, vessel arrival-time prediction and yard scheduling [7]. A recurrent industry claim is that such systems deliver large productivity and cost gains. Independent evidence is more cautious: a full-scale study by the International Transport Forum has concluded that automated ports are "generally not more productive than their conventional counterparts", and that port organisation, specialisation, location and size are more influential factors than automation; the achieved gains are mainly in consistency, safety and labour reduction, not raw moves per hour [6]. A survey of the operators of automated terminals also shows that the benefits that are most reliably realised are reduced performance variability and lower labour costs; reductions in unit handling costs are often overstated [7]. Thus, the balance of evidence does not support automation but is not against it either.

2.2. Digitalisation, data-sharing and the smart-port concept

A second strand enlarges the unit of analysis from the terminal to the port ecosystem. Based on the above, the smart port is defined as one that integrates physical automation with digital information facilities, process redesign and sustainability, and its concept has not been uniformly interpreted [1]. Port community systems and maritime single windows connect carriers, terminals, customs and inland actors through a shared digital platform, and are viewed as the prerequisites for achieving operational benefits, because much of the value of AI lies in cross-firm data visibility rather than in equipment itself. Composite tools, such as the smart-port index, have been proposed to evaluate the multi-dimensional "smartness" of operations, environment, safety and economy, but it is difficult to collect complete public data for them [8]. Literature on a maturity model for port digitalisation has begun to formalise the stages of digitalisation, but its leading work has not explicitly defined the connection between maturity and either performance or competitiveness [5].

2.3. Port competitiveness, measurement and GBA co-opetition

The third addresses the overall competitiveness of the port and the region through efficiency frontiers and multiple-criteria user preferences. Data Envelopment Analysis and Stochastic Frontier Analysis consider the terminal as a production unit that converts infrastructure inputs into throughput; a basic study has found that technical efficiency is related to scale, private-sector participation and a transshipment function [9]. Based on the results of a survey, the reasons for selecting a port and how competitive it is generally fall into four categories: efficiency, connectivity, hinterland conditions and cost [10]. At the regional level, a focused literature analysis of the GBA and Pearl River Delta as a multi-port system shows that Hong Kong's continuous decline relative to Shenzhen and Guangzhou is due to regional integration and policy, and international transshipment is recommended as a differentiated role [3]. Game-theoretic analyses of the same system conclude that a Hong Kong-Shenzhen coalition is beneficial to Hong Kong, but that Guangzhou is its main container rival [11], and efficiency comparisons across the terminals of the three cities show wide and uneven results [12]. The above research shows that competition and cooperation exist but address technology indirectly.

2.4. Synthesis: consensus, debate and the research gap

Along all three tracks, there is a general consensus that Hong Kong's decline is structural; connectivity and hinterland access are required for competitiveness; genuinely fully automated terminals account for a small proportion of the world's capacity; and digitalisation is strategically important [1, 3, 6]. Several questions are still unresolved: whether automation has shown a positive return on investment; whether AI is driving competitiveness or merely supporting it; whether Hong Kong can be repositioned as a high-value services and transshipment hub; and whether the integration of GBA should be viewed as complementary specialisation or zero-sum competition [6, 7, 11]. The clearest deficiency is the lack of a comparative, public-data assessment that places smart-port maturity alongside operational measures of competitiveness in the GBA—precisely the link that maturity literature has not yet tested [5].

3. Conceptual Framework

A three-dimensional operationalization is used to consider port competitiveness as a combined product of operational efficiency, network connectivity and smart-port or digital-governance maturity, rather than a binary "smart or not-smart" attribute [8]. AI and automation in this scheme are modelled as enabling factors; they affect competitiveness indirectly by facilitating changes in the operating model and, in cooperation with data-sharing platforms, ecosystem-level coordination. Competitiveness will be achieved only when the new technologies are connected to the hinterland, supported by good governance and skills, and when promoting green transformation (Figure 2). The three levels of maturity are based on the technology-organisation-environment approach; the final level of the latter is the institutional environment, and in the GBA, this includes the "one country, two systems" system [13]. Based on the above framework, if automation were a direct driver of competitiveness, automation maturity should track operational performance across cases; if it is only an enabler, no such relationship should appear.

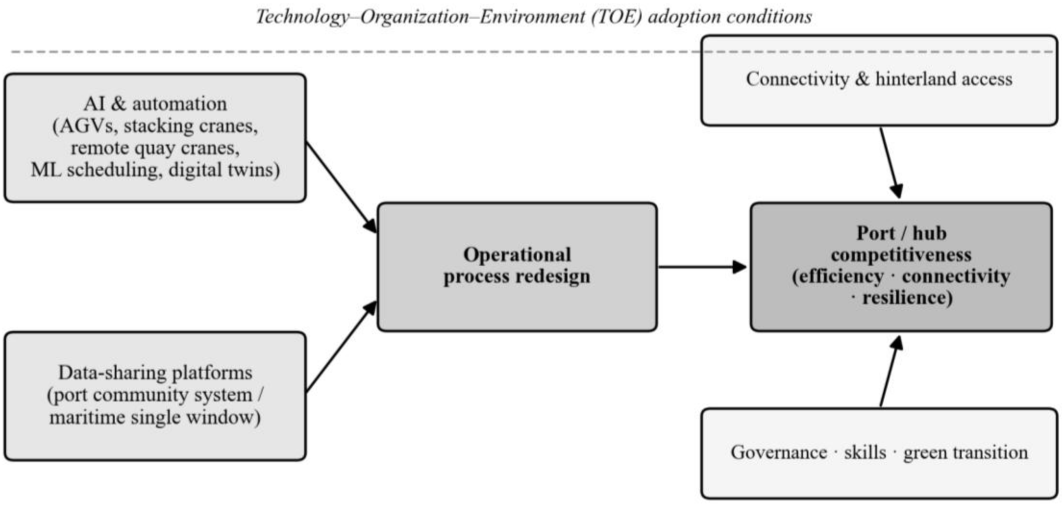

Figure 2. Conceptual Framework: AI and automation affect port competitiveness indirectly through operational process redesign and ecosystem data sharing, under the condition of connectivity, governance and the technology-organisation-environment (TOE) context.

4. Data and Methods

4.1. Research design and case selection

A Nested Comparative Design is employed. The primary samples are port- or port-area-level cases that have abundant publicly available data, and selected container terminals serve as sub-cases for mechanism tracing. Cases were selected to cover (i) the GBA cluster, (ii) a gradient of automation maturity, and (iii) both transshipment-hub and gateway functions, provided they were available in the public data. Hong Kong (Kwai Tsing) is the representative case. GBA rivals are Shenzhen and Guangzhou, and their Yantian, Mawan and Nansha Phase IV terminals are sub-cases; globally, automated-terminal benchmarks include Singapore (Tuas/PSA), Shanghai (Yangshan Phase IV), Rotterdam (Maasvlakte II) and Qingdao (Table 1).

Table 1. The Comparison Case Set.

Port (terminal)	Role	Operator / governance	2024 TEU (m)	Automation	Public data
Hong Kong (Kwai Tsing)	Focal; transshipment	HIT, MTL, COSCO-HIT, ACT (Seaport Alliance); private	13.7	Semi (yard only)	High
Shenzhen (Yantian; Mawan)	GBA rival; gateway	Hutchison; China Merchants (SOE)	33.4	Full (Mawan)	Moderate
Guangzhou (Nansha IV)	GBA rival; gateway	Guangzhou Port Group (SOE)	26.1	Full (BeiDou IGV)	Moderate
Shanghai (Yangshan IV)	Benchmark	SIPG (SOE)	51.5	Full	High
Singapore (Tuas / PSA)	Benchmark; transshipment	PSA (Temasek)	41.1	Full	High
Rotterdam (Maasvlakte II)	Benchmark	APMT; RWG (DP World)	13.8	Full	High
Qingdao (QQCTN)	Benchmark	Qingdao Port (SOE)	30.9	Full	Moderate

4.2. Indicators and data sources

Competitiveness has three tiers (Table 2). The operational tier uses annual container throughput and the World Bank-S&P Global Container Port Performance Index (CPPI), which ranks ports by vessel time [14]. The connectivity tier employs UNCTAD liner-shipping connectivity measures [15]. The maturity tier shows the scope of automation (gate, yard, quay), and each port is classified as semi-automated or fully automated according to the terminal-automation taxonomy in the literature [7], plus port-community-system status. Data are provided by the 2025 edition of CPPI, UNCTAD, Hong Kong Maritime and Port Development Board and port-authority and government records [4, 14, 15].

Table 2. Three-Tier Indicator Framework and Public Data Sources.

Tier	Indicators	Public source
Operational efficiency	Annual throughput (TEU); CPPI rank (vessel time in port)	World Bank–S&P CPPI 2025 [14]; port authorities
Connectivity	Liner-shipping connectivity (economy / port LSCI)	UNCTAD [15]
Smart-port maturity	Automation scope (gate / yard / quay); semi vs. full class; PCS / MSW status	Operator and government records; taxonomy [7]

4.3. Analytical strategy and limitations

Due to uneven cross-jurisdictional input availability, a uniform frontier estimate was not used; instead, the dimension data from each native public scale were collected and tiered for comparison, and qualitative process tracing was applied to interpret the mechanisms in the terminal sub-cases. Reported efficiency figures distinguish independent measurements from operator self-declarations. The analysis has three main limitations. First, only public data are available; port-level connectivity values for some GBA ports are missing, and some terminal records are provided by operators. Second, the design is associative and does not determine causality. Thirdly, the indices are not all the same; for example, CPPI only shows how long a vessel stays at a port and does not cover overall supply chain performance, so results need to be cross-verified at different levels rather than compiled into a single number [14].

5. Comparative Findings

5.1. Operational efficiency and connectivity

By scale, the GBA and East Asian gateways account for most of the cases (Table 3); Shanghai exceeded 50 million TEU and Singapore reached 41.1 million TEU in 2024, and Hong Kong (13.7 million) is now about the same as Rotterdam (13.8 million). However, the ranks of operating efficiency are not the same. In 2025, Hong Kong ranked 9th in the world, ahead of Singapore (21st), Shanghai (23rd), Yantian/Shenzhen (35th), Guangzhou (36th), Qingdao (101st) and Rotterdam (333rd) in the CPPI [14]. Where port-level connectivity data are available, the East Asian hubs remain highly connected; Hong Kong still has a strong economy-level connection position in line with its transshipment function [15], although its throughput has decreased. Therefore, the dimensions of efficiency and scale are different; Hong Kong has lost volume leadership but still maintains best-in-class vessel-handling efficiency.

Table 3. Cross-case Competitiveness Matrix.

Port (terminal)	2024 TEU (m)	CPPI 2025 rank	Connectivity (PLSCI, 2025)	Automation
Hong Kong (Kwai Tsing)	13.7	9	n.a. (economy LSCI 389.6)	Semi
Shenzhen (Yantian)	33.4	35	n.a.	Full / semi
Guangzhou (Nansha)	26.1	36	n.a.	Full
Shanghai (Yangshan)	51.5	23	2,434	Full
Singapore (Tuas)	41.1	21	1,859	Full
Rotterdam (Maasvlakte II)	13.8	333	952	Full
Qingdao (QQCTN)	30.9	101	1,367	Full

Note: The listed ranks of CPPI are for port and terminal entities of different granularities; port-level UNCTAD PLSCI has not been published for Hong Kong, Shenzhen or Guangzhou, and n.a. means not available.

5.2. Automation maturity and the competitiveness link

The maturity dimension does not align with the efficiency rank and is not correlated to it (Fig. 3). Hong Kong is the only semi-automated port in the sample; its automation is limited to remotely controlled yard cranes at a single terminal, and quay and horizontal transport are still manned [7], but it has achieved the highest operating-efficiency rank. Most all-automated benchmarks cover nearly the entire range of efficiency distribution, and the top two are in Singapore and Shanghai, while the bottom one is in Rotterdam. Automation level does not show a trend in operating efficiency. This is in line with the independent research by [6] that automation is not, in itself, a sure way to improve productivity, and thus should be regarded as an enabling factor whose benefits depend on the scale of stable shipments, cargo standardisation and institutional support, rather than as a standalone driver of competitiveness.

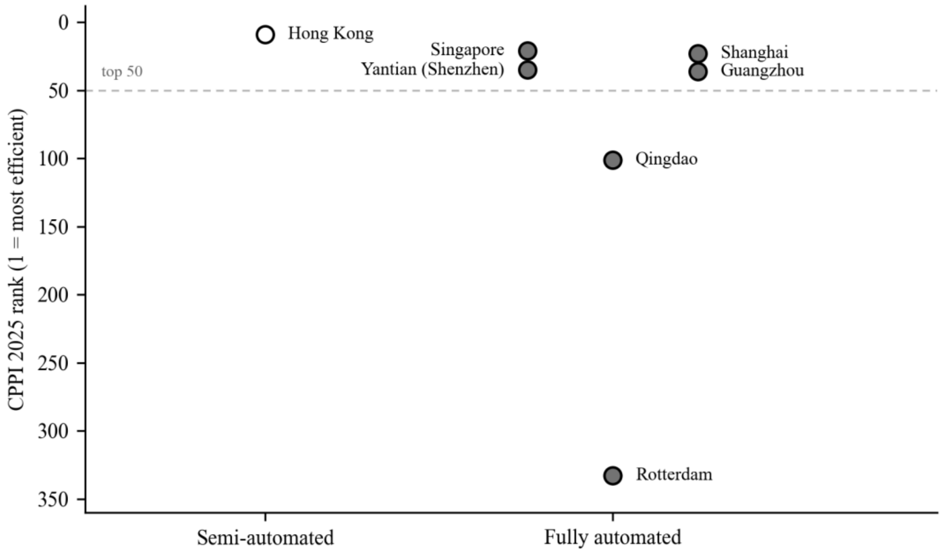

Figure 3. Container-terminal automation maturity versus operational efficiency (CPPI 2025 rank) for the case set. The single semi-automated port in Hong Kong has the best efficiency ranking, and fully automated ports are spread out. Sources: CPPI 2025 [14] and automation classification after [7].

5.3. Hong Kong in focus

Hong Kong's position can be regarded as having excellent operating efficiency but reduced structural competitiveness. The automation lag is indeed real, but it is not the immediate reason for the drop in quantity; according to the regional literature, this decline is due to hinterland and transshipment changes [3]. The port's strategic response has focused on cooperation and digital coordination, establishing a berth-pooling Seaport Alliance and a new port community system, and is now advancing higher-value maritime services rather than headlining terminal automation [4]. On the other hand, the GBA and global benchmarks have achieved full automation (BeiDou-guided vehicles in Nansha, brownfield 5G conversion at Mawan, and AGV-based terminals in Yangshan, Qingdao and Tuas), but their operating-efficiency rankings vary widely, indicating that automation is neither required nor sufficient for high efficiency.

6. Discussion

The most obvious result is that the least automated port in the sample has the best operational efficiency rank, and fully automated ports are spread across all ranks; thus, a mechanism is required. The CPPI indicates the time vessels spend in port and is affected by berth productivity, call-size mix and congestion, but not by equipment automation [14]. The recorded benefits of automation are mainly in terms of consistency, land productivity and labour reduction, not in faster vessel turnaround, and they are conditional on high and stable volumes, standardised cargo and high local wages [6, 7]. Hong Kong's privately owned, transshipment-oriented terminals are designed to meet the demand for fast vessel turnaround and are therefore rewarded by the CPPI; a basic efficiency study has linked this exact profile—scale, private operation and a transshipment function—with high technical efficiency [9]. Therefore, the decoupling is not abnormal but expected: automation and vessel-handling efficiency are independent factors, and the headline productivity increase due to automation has often not been realised in the independent evidence [6].

Hong Kong is a typical case, however. The port's binding constraint is no longer vessel-handling efficiency, which is still world-class; rather, it is volume and structural role, and the throughput has dropped by about one-third since 2018 due to the erosion of its transshipment function by direct mainland deep-sea services and hinterland access [3]. As the cause of erosion is cargo geography rather than berth speed, closing the automation gap will not reverse the volume trend; a fully automated Hong Kong terminal will still have the same hinterland and cost disadvantages. The more promising levers are to leverage the port's existing strengths, build a digital coordinated ecosystem through the new port community system, deepen cross-modal integration of sea-land-air, and shift towards high-value maritime and logistics services [4], rather than pursuing capital-intensive terminal automation for its own sake. Therefore, the "smart port" mentioned in the policy discourse may focus too much on automation, and the actual incremental gains for Hong Kong are more likely to be found in data sharing and coordination.

At the regional level, the results indicate whether the GBA is to be regarded as zero-sum competition or cooperative specialisation. These cases differ systematically in function, that is, transshipment hubs versus gateways, and in efficiency; mainland ports have grown by directly connecting to the hinterland rather than by developing Hong Kong's transshipment model. This pattern is consistent with a division of labour where Hong Kong focuses on foreland and transshipment, while Shenzhen and Guangzhou serve as the hinterland; game-theoretic analysis of the same system has found a rationale for this division and identified Guangzhou as Hong Kong's primary container rival [11]. Although such specialisation is desired, it poses a governance problem as much as an economic one: the mainland ports have been integrated under provincial state-owned enterprises, while Hong Kong operates independently as a private entity within a separate customs and regulatory system in "one country, two systems". Therefore, cross-border coordination—such as sharing data platforms, standardising customs procedures, and jointly planning capacity—requires overcoming the institutional barriers mentioned above, and this is precisely the dimension that the technology-organisation-environment perspective highlights [15] and the one least suitable for purely technological remediation.

The two main implications are as follows. First, the concept of competitiveness has been decomposed into operational efficiency, connectivity and smart-port maturity to avoid the common error of equating automation with competitiveness; otherwise, a single composite score would have obscured the disparity that is the main finding. Second, the evidence advises against ranking ports by a single index: CPPI reflects only vessel-side efficiency and fails to consider hinterland reach, supply-chain role or service value; thus, multiple measures need to be triangulated [2, 14]. These claims have clear limitations: the design is comparative and associative rather than causal; several port-level connectivity values are unavailable; some terminal records are operator-reported; yet, the qualitative pattern that automation maturity and competitiveness are loosely coupled holds true across all the public indicators presented here.

7. Conclusion

Across operational efficiency, connectivity and smart-port maturity, automation maturity and operational competitiveness are loosely coupled; the least automated port in the sample is the most efficient, and the fully automated benchmark covers the range of efficiency. Therefore, the relative decline of Hong Kong can be better explained by structural and connectivity factors than by an automation gap, and AI is more likely to be an enabler than a driver of competitiveness. In the future, these associations will be tested using terminal-level operating data, the new cross-boundary port community system will be evaluated as it matures, and the GBA co-opetition analysis will be updated with post-2024 data.

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