© JAN 2026 | IRE Journals | Volume 9 Issue 7 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I7-1713908

End-To-End Analytics Across Ports, Customs, Warehouses, Last-Mile; ETA Prediction and Bottleneck Detection at Scale.

SYED HASSAN
Institute of Business Management, Karachi, Pakistan
ORCID: 0009-0009-3076-6043

Abstract- ***The need for a comprehensive and reliable logistics system performance has been driven by the interrelations and interactions among seaport/terminal operations, customs and border protection organizations, warehouses and fulfillment centers, and last-mile delivery. To report these events and handle the fast pace of events, each subsystem has high-velocity events such as AIS reports, gate operations, inspection notifications, scans, and GPS location updates. These events can now be used to produce a series of events for predicting the possible arrival times and reporting possible congestion. This systematic review collated and collated the study and analysis by collecting different articles and studies related to logistics performances in the period covered by this systematic review, namely, from 2020 to 2025, namely, related to: (i) two-stage ETA prediction models that can include sea and overland components, related to bottleneck analysis and explanation for causations for delay propagation, and related to logistics architectures to make simulations and facilitate systemization and deployment. To outline systematic reviews following the procedure by Page and associates in 2021 and extensions by Rethlefsen and associates in 2021, articles and the highest quality studies in logistics and related topics have been collated. Based on the systematic reviews, based on articles that this systematic review has collated, extremely valuable and practical approaches emphasize event and entity time and uncertainty analysis, traceability, and analysis based on governance structures.***

Keywords: Supply Chain Visibility; Control Tower; ETA Prediction; Port Congestion; Customs Risk Management; Warehouse Analytics; Last-Mile Delivery; Bottleneck Detection; Digital Twin; Systematic Review.

I. INTRODUCTION

"World-class supply chains are increasingly being evaluated not only for their cost, but also for their dependability, traceability, agility in the face of disruptions, and speed of recovery." This could result in a non-linear effect in the distribution of delays, such as "delay in container ports, chain delays in inland transport carriers, uncertainty of border crossings, capacity of storage, and last-mile issues," making it hard to "achieve optimization without analytics." The Review of Maritime Transport 2020 underscores risks in the pandemic era and communicates a paradigm "to give paramount importance to digitalization" (UNCTAD, 2020). To deal with these issues, a great deal of effort is being made by standardization bodies and associations to ensure a level on event data interoperability and optimized port calls. ((IAPH), 2024) The structure for track-and-trace standardization is intended to guarantee a common set of event semantics and identifiers to enable carriers, port organizations, inland, or shippers to correlate events to a related shipment timeline (DCSA, 2020). Port call standardization and just-in-time arrival behaviors are enabled to minimize days of wait time, idle hours, and emissions (IMO, 2023; IAPH, 2024). These are encouraging a favorable context for operating analytics programs over a fully managed supply chain control tower application, typical during operational day-to-day policies, largely enhanced by multiple party events. Although there is some level of connection addressed now, it can be said to be a quite fragmented area of study. (Digital Twins in the Context of Seaports and Terminal Facilities, 2024) The investigation of congestion models at the port level and the eta-assist function in predicting ETA can be addressed separately from analytics associated with customs clearance, warehouse through-put prediction, and last mile eta prediction. (Liu et al., 2026) Additionally, it has been observed that the strategies for assessment also diverge in some way. (Khazzar et al., 2025) The performance appreciates in the models pertaining to leakage in a drift deployment setup. (Alam et al., 2026) The attempt at the literature study

in the thesis proposes a collective investigation of all these aspects by identifying eta prediction in a multi-step process from the time of arrival and discharge of the ship until the time of customs clearance and then until the time of warehouse processing until finally the time of the last mile/line haul eta prediction function in pinpointing where the bottleneck lies in the process with the aim of identifying the levers associated with the extracted time.

1.1 Purposes of this Study

In order to comprehensively examine (2020-2025) the state-of-the-art for end-to-end logistics analytics with a view of ports, customs, warehouses, and last-mile delivery, and then design an integrated set of key performance indicators that link eta prediction techniques with scalable bottlenecks.

1.2 Aims of the Research

- Identification of critical data sources and standards for shipment-based timeline events in nodes.
- Compare models that predict ETA in instances involving multiple routes (maritime routes, border routes, warehouse routes, last-mile routes).
- Integrate bottleneck discovery algorithms such as Queueing Theory, Process Mining, Causality Inference, and Digital Twin concepts in an attempt to understand delay propagation.
- Examine different assessment processes from the perspective of realism in assessment, keeping in mind splits in time and/or
- Create an integral perspective of KPIs that incorporates time, costs, risks, and carbon over end-to-end processes.
- Formulating guidelines for control tower application with regard to architecture and management.

II. BACKGROUND AND CONCEPTUAL FOUNDATIONS

“End-to-end logistics analytics involves a process with socio-technical features, where the technological feasibility is linked with information integration,” whereas “the fulfillment of economic value is based on a governance choice.” The four concepts that comprise the principles are:

Firstly, event visibility. As far as shipment life cycles are considered, their lifecycle can be sufficiently described using an event log with corresponding events and their positions in time. A homogeneous event log fails to exist without an entity resolution, using parameters such as container numbers, BOL numbers, shipment numbers, and couriering tasks. (Fu et al., 2025) Industry standards for event definitions and development of interfaces for DCSA target compatibility among track and trace systems, which remain non-centralized. (DCSA releases Track & Trace Interface Standard version 2.2 with new subscription capability, upgraded security, and support for document events, 2025) The standards have been developed from version 1.1, issued in 2020.

Second, ports and sea legs. Analysis of AIS data for all vessels simulates the route, stay time, and dynamics of vessel calls at each berth, and current studies aim to apply deep-learning models for predicting levels of congestion and estimating levels at ports based on AIS data analysis, interpreting AIS data on congestion levels and Erlang series predictions for dynamics (Maritime Policy & Management, 2022). ETA prediction models have been enhanced, and stacking decision trees on AIS data may enhance ETA predictions (Saber et al., 2025). In reality, the ETA of the vessel is just one part of many that play a significantly important role since discharge operation, yard capacity, and rate will always have a downstream impact that will be of less importance than ETA predictions for sea legs.

Thirdly, border clearance and customs activities. Customs agencies are increasingly turning to analytics to achieve a good balance between facilitation and enforcement. In the literature, it has been shown that using external business data to improve linked risk decisions for customs has clear added value but requires data quality evaluations to define the opportunity for linkages (Hofman et al., 2021). In the current issue of the World Customs Journal, a technology-oriented perspective introduces the possible applications of “AI/ML & Network Analysis" in risk scoring, outlier identification, or post-clearance audit. On the one hand, they explain the restrictions on applying such technologies to regions of their application, such as explanation, skills, or a suitable administrative framework (Vijayakumar, 2025). The

end-to-end customs ETA process could also represent a highly variable process where tail activities of the type of exceptional inspection or verification activities could have a most risk-influencing role in the delivery of the final result of the process. (Johnson, 2025) Fourth, inland fulfillment and last mile. Warehouse fulfillment produces scan-level WMS/WCS events and Internet of Things (IoT) telemetry, which supports the analysis of throughput and the identification of bottlenecks. In the last mile domain, learning-based models for ETA and routing have progressed, and comparisons across a broad set of data are feasible. (Ruiz-Fas et al., 2026) The challenge dataset, LaDe, illustrates the efficacy of task events and courier data for ETA tasking and its support for the assessment (Wu et al., 2023). Each of these building blocks requires an integrated understanding that leads to the prediction of an aggregate of stochastic stage durations with shared risk factors and covariations in the event of disturbances. (Zheng & Brintrup, 2025)

III. METHOD

Our systematic review was conducted based on a systematic review protocol harmonized with the PRISMA 2020 proposal by Page et al. (2021). Our search procedure adhered to the PRISMA-S proposal by Rethlefsen et al. (2021). The topic of interest for us involved end-to-end analytics with a scope of focus on at least two nodes, including ports/terminals, Customs/Borders, warehouses/fulfillment centers, and last-mile delivery. The inclusion criteria for us involved studies related to the prediction of ETA, modeling of delay propagation, congestion modeling, bottleneck identification, and Control Tower designs.

3.1 Search strategy

A range of phrases such as "ETA prediction", "port congestion, "customs clearance time", "warehouse throughput prediction, "last mile delivery ETA", "control tower, "process mining", and "digital twin" were used to investigate multidisciplinary databases and publication sites. Interoperability milestones and/or KPI ideas, such as those contained within IAPH, were taken from standards and reports written by respectable bodies such as UNCTAD, IMO, and DCSA when applicable.

3.2 interoperable milestones or KPI approaches.

3.2 Inclusion/exclusion criteria

The sources considered for the study (i) had publication dates ranging from 2020 to 2025, (ii) related to methods, data, or systems concerned with ETA prediction or bottleneck detection, and (iii) had enough technical content related to data or variables used in the study. Non-credible sources, along with non-transparent sources/publications, were eliminated.

3.3 Screening & Quality Appraisal

The search included titles and abstracts for relevance. Full-text search was conducted. An appraisal checklist was utilized: Provenance as well as Representativeness of Data. Splitting Approach: Time/Entity. Uncertainty Expression. Constraints of Deployment: Latitude and Latency.

3.4 Synthesis approach

For each case, we had mixed results (MAE/SMAPE score for ETA, queue length for congestion, throughput for warehouses), so we did narrative synthesis. These details were extracted from each case: node coverage, number of modalities, model family, design of evaluations, operational choices addressed, and importance of KPIs. Aggregated results were received by an integrated KPI taxonomy.

IV. TAXONOMY OF ANALYTICS CAPABILITIES

Literature review on this task can be categorized into five capability levels, with each capability level being capable of end-to-end ETA prediction and detection of the bottleneck altogether. (Jahin et al., 2023)

Data and Interoperability

Many of the failures of functioning analytics relate to the absence of a standard definition of milestones and entity resolution. (mpotepa, 2017) The requirements of traceability relate to standard definitions of relevant events and recognition of entities to relate them (DCSA, 2020). In port operations, there is an understanding of the standard definition of port calls to enable standard arrival times to synchronize allocations (IMO,2023; IAPH, 2024). In addition, for the custom Authorities, links to external business data

may improve risk targeting, although data analysis is required (Hofman et al., 2021).

4.2 Multi-stage ETA prediction

ETA can be viewed as a sum of stage times with distributional shifts based upon factors such as weather, congestion, labor, and policy. ETA for seaport arrivals with high accuracy is possible by tree-based stacking with sequences of AIS and ensemble learners (Saber et al., 2025) when constructed with variables involved in distance, speed, and routes. Last mile studies and applications of ETA and routing with deep learning have indicated that task-event logs with a larger depth result in a forecast increase (Wu et al., 2023). The generalization is that a precision of one leg is not enough to guarantee end-to-end because correlations between stages and hand-offs tend to have a last mile effect.

4.3 Bottleneck Detection & Delay Propagation

Bottlenecks may also be quantified with regards to peaks of use, growth of queues, or process mining "rework loops." Digital twin models merge event logs and use-driven bottleneck analysis. This merging of process mining makes it possible to discover bottlenecks of process throughput. The above-stated principles may also be applied in a logistics system. In this system, "bottlenecks are temporarily mobile: They need to be constantly and probabilistically located," which makes it possible for simulation projection of forecasted mitigation of areas with expected bottlenecks.

4.4. Risk analysis at border crossing

Border clearing is a high-variance process. Technology-centric customs risk management explores supervised/unsupervised learning and network analysis in reference to governance constraints for anomaly detection (Vijayakumar, 2025). There exists supporting evidence to conclude that the use of outside business data may provide value so long as data use-value assessment is properly evaluated (Hofman et al., 2021). Regarding fully automated ETA processing, it has been hypothesized that in border clearing, drivers of inspection probability/completeness of records signal distributions regarding clearance time may be accurately depicted.

4.5 Control Towers and Scalable Decision Support

These control towers in supply chain management are intended to leverage inter-party data synergies. For control towers, critical success factors, including data, governance, analysis, and adoption, have been specified by a systematic review in 2024 (Chaffin et al., 2024). For control towers in 2025, based on an interpretive study, it is restated that analytics are important in real-time analytics, while in disruptions, analytics are essential in control tower performance (Gunasekaran et al., 2025).

V. INTEGRATION INTO THE KPI FRAMEWORK

A good control tower should be provided with a KPI spine that distributes a minimum level of comparability of data at all nodes. The suggested level of KPIs can be used at the ports, customs, warehouses, and in the last mile delivery as follows: (i) time/reliability, (ii) cost utilization, (iii) risk compliance, and (iv) carbon sustainability metrics. JIT arrival pilot programs in ports and seaports together address time saving along with carbon saving by emphasizing the need to reduce the idling hours at the anchorage point or the IMO hours by the greatest possible margin (IMO, 2023; IAPH, 2024). Data quality KPIs in customs and inter-operability are included within the study. The models construct the notions based upon the fitness for use of external business data (Hofman et al., 2021).

VI. EVIDENCE SYNTHESIS: WHAT WORKS & WHAT BREAKS AT SCALE

6.1 Realism and Leakage Control

In Generally speaking, one of the threats to validity for all application tasks would be summarized as the phenomenon of "evaluation leakage," test and train on the same objects or time segments, also unrelated to the domain application task. Time splits and entity-held-out evaluation prove to be critical with respect to ETA systems since the environment varies per season, based on worker number and route. The demand for generalization verification of a city and courier level would require industry-scale last-mile datasets. Congestion scores, based on AIS at the ports, would have to be handled with care about geofencing in order not to provide biased classes for the scores in case of their use with missing signals.

6.2 Prediction + diagnostics (actionability)

Precise information on ETA will be useful only where complemented by insights to reduce it. A specific example of bottleneck analysis for a digital twin can propose a generic approach to utilizing logs of coupling events, simulation, and process mining to highlight what resources the basic drivers of bottleneck constraints are. This, in application to logistics process domains, would need a stage-level break down of components of predicted ETA metrics to appropriate levers such as slotting of berths, inspection prioritization, employment of human resources, and re-routing.

6.3 Customs analytics as a delay amplifier/reducer

Custom High variance in clearance, hence filling out the documents and controlling risks of document completeness before clearance is an area of high potential. Evidence does show how a combination of external business data with public data produces positive value (Hofman et al., 2021). Combining from a technologically based perspective, customs risk management may be defined as labelling, adversaries, and explainability of enforcement limitations (Vijayakumar, 2025). The limitations talked about above do mean that the ETA system models will use clearance time combined with regimes - green lane versus inspection - with probabilities based upon those regimes.

6.4 Adoption/Governance of control

Success has been achieved on the part of Control Towers when it comes to adherence to alert budgets, escalation playbooks, and authority to act. Driver analyses about the drivers have been focusing on issues to do with integration maturity and cross-functional governance. To them to be applicable, there is a requirement for models together with ownership of key KPIs, model monitoring, or closed-loop feedback relating to recoverable time, avoided demurrage, OTIF, and idle emissions.

VII. DISCUSSION AND DESIGN PRINCIPLES

Based on this summary of findings, the following design principles are hereby provided for practitioners and researchers:

1) Data product or 'event time' must come first before models. ER and milestone semantics are to come first before correct ETA and diagnostics.

2. Model ETA with multi-stage graph, forecast is not only a point ETA but also stage distributions.

3) Combine learning process with operational constraints, add the capacity indicators: berth slot, inspection staff, shifts. Add alert budgets.

4. Continuous bottleneck diagnostics: Perform shifting bottlenecks analysis by process mining and simulation on digital twins for validation, found solution for those problems.

5. Line up KPIs with decision-making. A KPI framework unhooked from any decision-making activity will render analytics no more than a useless act of a dashboard.

6. Govern for drift and accountability: Because the control tower applications are compute-heavy, audit logging, model tracing, and decision rights should exist with both parties. Chaffin et al., 2024; Gunasekaran et al., Those guidelines extend the research agenda to multi-node data sets, the valid assessment of stress tests concerning the temporal dimension, carbon-related analytics, considering JIT arrival times, and waiting times with a reduction of emissions. IMO, 2023; IAPH, 2024 8. Conclusion This report's systematic review has compiled various studies using analytics for end-to-end logistics from the year 2020 to 2025. Therefore, the most worthy warehouse techniques should be composed of: (1) shipment-centric Event-Time data products using sharable standards; (2) Multi-Stage ETA Models handling Changes in Context and Uncertainty Modeling; (3) Bottleneck Analyses marrying Event Logs with Process Mining and digital twin simulation models; and (4) Management structures connecting Predictions to Decisions using Control Tower Models. In general, the KPIS structure presented in this report proposes an effective road map toward building either Predictive/Prescriptive Decision Support.

Figure 1. Reference Architecture for End-to-End Logistics Analytics
A deployment-oriented architecture connecting event sources to data products, models, decisions, execution, and governance.

© JAN 2026 | IRE Journals | Volume 9 Issue 7 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I7-1713908

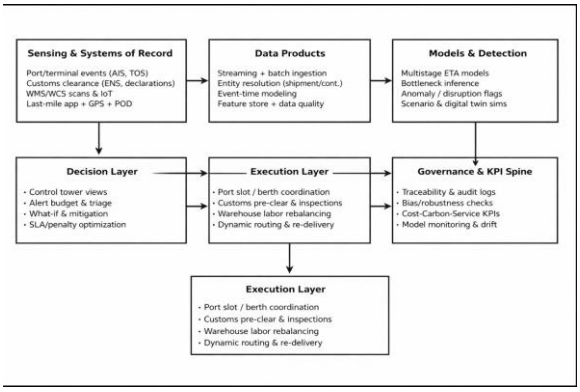

Table 1. End-to-End KPI Spine and Analytics Methods

Node	Key time KPIs	Reliability KPIs	Cost/utilization KPIs	Carbon KPIs	Typical analytics
Port/Terminal	Anchorage wait; berth-to-gate-out	On-time berth; congestion index	Crane productivity; yard utilization; demurrage	Idle emissions; JIT adherence	AIS+event logs; congestion DL; simulation
Customs/Border	Clearance time; inspection cycle	Release probability; exception rate	Inspection capacity; rework	Avoidable trips; paperless proxies	Risk scoring; anomaly detection; NLP
Warehouse/Fulfillment	Put-away to dispatch; pick/pack	SLA hit; backlog volatility	Labor productivity; dock utilization	Energy intensity; wasted travel	WMS analytics; process mining; digital twin
Linehaul	Departure-to-arrival at hub	Delay risk by corridor	Vehicle utilization	Fuel intensity; empty miles	Traffic/weather fusion; ETA models
Last-mile	Out-for-delivery to POD	ETA error; first-attempt success	Stops/hour; reattempt cost	Emissions/stop; miles/delivery	Spatio-temporal ML; dynamic routing
End-to-end	Order-to-delivery lead time	OTIF; tail risk (P95)	Total logistics cost; penalty exposure	CO2e/shipment; waiting emissions	Causal graphs; scenario sim; control tower

Node-by-Node Synthesis of End-to-End Logistics

9.1 Ports and terminals (arrival uncertainty, congestion, and hand-off delays)

Port analytics has moved from basic analytical reports, such as cargo handling data on a monthly basis or average dwell time, from 2020 to 2025, to high-frequency, predictive, or event-based analytics. (Khazzar et al., 2025) With more data available on events, such as Automatic Identification System (AIS) or Terminal Operating System (TOS) data, predictions of the length of anchored queues, berth availability, or ship turnaround times can be made on an hourly or near-real-time basis. There has been a major advancement in constructing models of traffic congestion patterns in ports using these advances. More recent research has shown that the application of congestion modeling through deep learning methodologies incorporates berth-to-berth vessel movement information and enables the estimation of congestion indicators for the analysis of future berth usage (Maritime Policy & Management, 2022). Such

analysis would be highly useful for triage in the operation of terminal choice and congestion at seaports, which can have spillover effects on hinterland infrastructure, such as road and rail transport. In the above context, the Estimated Time of Arrival (ETA) is treated as a point estimate. However, the Estimated Time of Arrival may be considered a combination of related time variables such as the arrival time at the port limits, the assignment of berth time, the start of cargo operations, and the gate-out time. The above time variables are affected and depend on a number associated with factors to the operational system. According to the literature study, interdependence can increase accuracy and decision support throughout the Estimated Time of Arrival. By applying this methodology, waiting times for ships to take anchorages can be decreased by applying indicative arrival times appropriately to match available berth windows rather than adhering to nominal arrival times (IMO, 2023; IAPH, 2024). Consequently, it gives an indirect contribution to lower fuel consumption and emissions by reducing idle times when ships are anchored. The second major problem for a port is hand-off friction. The reality is that a big chunk of delays cannot be blamed on capacity alone but rather on process-related aspects such as incompleteness of documentation, unsynchronized implementation of operational orders, mismatched cut-off times, and varying definition of milestones. The problem of semantics and standardization in track-and-trace systems, particularly the definition of milestones based on meaningful business-process events, has been widely discussed in the literature. As far as end-to-end logistics analytics is concerned, a port functions as both an input point for congestion and time-slot allocation models and an output point for multi-party coordination processes.

9.2 Customs and Border Control Procedures: Risk Targeting and Variance Reduction

It has been recognized that analytics may play a role in generating differentiated predictive probability models for the length of Customs clearance and the risk of a secondary inspection. The application of analytics in Customs, the studies suggest, requires the development of a richer data set that may include the trader's compliance record, the specifics of the commodity, and business key performance measures. Nevertheless, in the general Data Fitness-for-Use paradigm, the use of external business data has several important questions related to public value. For example, customs administrations have to evaluate the effectiveness of enforcement efforts against those related to trade facilitation, because improvements in risk analysis cannot create unnecessary friction in low-risk value chains. The literature on risk management, with a focus on technology, draws attention to the growing adoption of artificial intelligence approaches, such as machine learning, for anomaly detection, as well as the risks associated with network indicators in customs administration processes. However, it is also seen as stressing the challenges of labeling outcomes in practical enforcement processes for AI systems (Vijayakumar, 2025). To model end-to-end ETA, customs clearance activities could be represented as a mixture distribution for risky profiles, including fast lane, documentary checks without physical inspection, and inspection routes with multiple services. The identification of a bottleneck at customs, in contrast with standard port congestion, entails a policy capacity bottleneck, with staff allocation and selectivity policies immediately impacting capacity. This, in turn, complicates the evaluation criteria for key performance indicators, requiring both clearance times and reliability, release, and exception rates to be considered. From a control tower perspective, having the capability to predict selectivity policy changes related to capacity allocation comes into play, considering the possibility that delays could cascade to warehouses and last-mile facilities for final delivery.

9.3 Warehouses and fulfillment (throughput constraints and rework loops)

For a warehousing and fulfillment operation, bottlenecks may originate from differences between the labor available compared to the capacity of the materials handling equipment, including the use of conveyor systems, as well as from processes involved, such as rework, staging, or order consolidation issues. In contrast to ports and customs, which may take years to implement changes, bottlenecks pointed out within a warehousing operation could, to a certain extent, be managed within a short period of days. For these reasons, effective methods for detecting bottlenecks in a warehouse are integrated with prescriptive analytics.

© JAN 2026 | IRE Journals | Volume 9 Issue 7 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I7-1713908

Digital twin techniques are getting a boost to synchronize analysis of event logs with 'what-if' analysis so that constrained resources on which warehouse throughput depends can be identified. Moreover, recent literature on throughput analysis points out the possibility of forecasting possible bottlenecks by means of leading indicators. Warehouses are also a point where Chathamodularizes the uncertainty that exists upstream into a commitment downstream for last-mile delivery. Warehouses require end-to-end service for effective staging and allocation of the inventory. This service requires early notice of the expected time of the shipment. This expected time is not standardized; therefore, warehouses use multiple-stage ETA estimations that are based on the uncertainty that exists in the expected time. In a full end-to-end network, warehouse analytics is also that connection that provides a solution to the uncertainty that came earlier. While there is uncertainty in regard to gate-out and release into the port, helping to decrease it is the warehouse through its planned assignment of goods to stages, assuming that the warning has been received. In this case, multistage ETA models are also required to create uncertainty at a stage level.

9.4 Last-mile delivery (High-volume prediction under human and curb variability)

Last-mile ETA is proven to show high volumes, high variability in space, and a dependence on human behavior factors such as driver skills, customer availability, and kerbside lead. The literature presents models for ETA and sequencing based on deep learning. Task-event logging is an essential part for last-mile traceability in large volumes of deliveries and is mentioned in Wu et al. (2023). Perhaps the most valuable insight from a holistic analytics point of view and a key factor for end-to-end analytics lies within the dependencies of the last-mile and associated delays and reduced windows for delivery costs related to lost attempts. As a result, a control tower handling last-mile processes would highly benefit from two inter-linked forecasts: (i) arrival times for readiness of the last mile, and (ii) probabilities of completion of the last mile based upon times of readiness. Bottleneck analysis would focus on congestion-related saturations (stops per hour, number of messengers) and exception groups (packages yet to be delivered) for the last mile.

X. METRICS, BENCHMARKS, AND REPORTING RECOMMENDATIONS

ASA/reliability: While discussing ASA/reliability on behalf of ETA-systems, it is necessary to define how ASA/reliability will be measured. Whilepoint scores such as MAE or RMSE are good but not adequate when important judgments revolve around service levels or tail risks, we suggest assessing ETAsystems based on: (i) prediction intervals (80%/90%), (ii) quantile errors(P50,P90), or preferably through calibration graphs of probability forecasts or decision-oriented scores such as 'recall@alert budget'in the case of bottleneck alerts. An example is: assessing the skill of the ETA-system-port congestionforecaster based on how well it predicts the top K hours in which the congestion levels are likely to breach a certain congestion level as opposed to minimizing the squared errors. Honesty and replicability are emphasized in PRISMA systematic reviews. According to the PRISMA 2020 guidelines, there must be in-depth documentation of selection, appraisal, and synthesis (Page et al., 2021). One variant of the PRISMA guidelines is PRISMA-S, which provides a checklist for documenting the reporting of the search strategy and can be easily reproduced (Rethlefsen et al., 2021). As for the area of logistics analytics, it is suggested that the documentation for empirical studies include: Split strategy: temporal splits and splits by entities. Data span for each season. Sensitivity for changes in customs selectivity.

XI. IMPLEMENTATION ROADMAP FOR PRACTITIONERS

In general, there will be four levels of the end-to-end analytics implementation scale.
Stage 1: Foundations of Visibility

Most of Definitions of milestones and an event log that incorporate identification for all nodes have to be developed. The usage of interoperability standards wherever possible (DCSA, 2020) must be considered, and the KPI for the data quality must be developed. This stage will see the organization meeting the target of developing the dashboard and the exception report.
Stage 2 — Predictive ETA and Early Warnings

© JAN 2026 | IRE Journals | Volume 9 Issue 7 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I7-1713908

This stage is Introduce multistage ETA forecasting models to forecast readiness times at critical hand-offs. Modular models are included per stage (Vessel ETA, clearance time, warehouse processing time, and final ETA) and integrated via a shipment graph. Emphasize on the splits with a focus on time, the reporting of uncertainty, and drift analysis. Secondly, the incorporation of congestion factors and berth windows at the ports (Maritime Policy & Management 2022; Saber et al. 2025). Lastly, at the customs stage, the probability of inspection and the corresponding conditional times (Hofman et al. 2021; Vijayakumar 2025).

Stage 3 - Bottleneck diagnostics and what-if analysis: Use diagnostic analytics to indicate the contributors to the delay and the probable root causes. Use process mining and Digital Twin analysis for What-if Analysis without having to execute the corrective measures (Kumbhar et al., 2023; Ragazzini et al., 2024). This is where playbooks in the control tower need to play a definitive role. There needs to be an indication or mapping of the alarms to the activity (berth slot allocation, pre-clearance checks, labor rebalancing, and rerouting) and ownership.
Phase 4 - Closed-loop Optimization: From acts based on alerts to integrated actions with a collective measurable outcome. In order for closed-loop systems to function, there must also be a requirement for governance. The success factors for control towers, discovered by literature, must also be measurable to facilitate adoption, including data integration, governance, analytics, and adoption (Gunasekaran et al., 2025; Chaffin et al., 2024). The goals of sustainability can also be included in the strategy by combining the decrease of waiting times with the decrease of emissions by taking advantage of the JIT arrival times, along with the idle time reduction strategies, according to IMO, 2023, and IAPH, 2024.

XII. LIMITATIONS

This literature review would be affected by the differences in outcomes and varying levels of data accessibility, especially in customs and warehouse systems. It would be difficult to generalize from the outcomes in terms of limited time scales and geography, given that many of these consequences are about routing and policy, and that generalizing from the outcomes would be challenging. The industry has best practices in terms of standards and reports, rather than the peer-reviewed literature, so it included some information pertaining to the understanding of milestone events and approaches in KPI, but perhaps not efficacy.

XIII. CHECKLIST FOR A PRACTITIONER IMPLEMENTING END-TO-END ANALYTICS

The following checklist translates the results from the literature review into practice, developing questions for teams to answer during the design and implementation stage.

Data & Interoperability

- Are there shipment-oriented events captured in an event log with clear milestones and identifiers for late-arriving shipments? (DCSA, 2020)
- Can the abilities to resolve entities, as well as the quality of data, be quantified: match rate, ambiguity rate, node-level data quality KPIs–ports, customs, warehouses, LM)?

Modeling & Evaluation

- Are ETA models created as multi-stage distributions for predictive intervals, and is tail-risk P90/P95 monitored?
- Are the training and test data splits splits of the timeline, holds-out validation on entities, and do the test series include stress situations (seasons of peak use, disruptions, policy changes)? (Page et al., 2021)
- Is uncertainty utilized as a gatekeeper for alerts, thus preventing 'false certainty' in the control tower?

There are no questions associated with R1.

Bottleneck detection & actionability

- Will the bottleneck alerts allow breaking down the waiting time into thestag contributors and tracing the contributors back to the applicable action trigger (berth window, inspection triage, labor shift, or route plan)?

- Does it have a 'what-if' analytical capability for modeling and testing mitigation actions before being applied on a broader implementation scale (Kumbhar et al., 2023)? Governance And Adoption
- Are audit logs, monitoring of models, and drift triggers in place along with escalation playbooks (Chaffin et al. 2024; Gunasekaran et al., 2025)?
- Are business results (recoveries of time, prevention of demurrage, enhancements of OTIF, reductions of idle emissions) being measured and controlled within a continuous improvement process?

CONCLUSION

The above systematic review has considered the state of the art in end-to-end logistics analysis during the period 2020-2025, with a focus on the following subjects:

The ports, customs & border protection, warehouses & fulfillment centres, and last mile. Overwhelming evidence exists to indicate that logistics optimization cannot be effectively achieved node by node, but as a function of multi-node interactions in the form of ship-centric events with ETAs forecast over multiple stages and continuous bottleneck analysis across the entire value chain. From this analysis, there are four pillars appearing in the literature that keep on appearing, which enable the analytics: strong entity resolution event-time data products that can be standardized and scaled across the enterprise, eta models that have uncertainty, correlation, and change in the nodes with multiple phases; a method of detecting the bottlenecks combining processes, queuing theory, simulation, and the digital twin, which could understand the influence of delays; and governance/controls which could be translated from the predictions with playbooks clearly defined. Without the pillars, analytics will continue to be more descriptive, not robust, nor connected to controls. The review also underlines that customs and border processes are delay amplifiers and reducers in holistic end-to-end networks for their high variance and capacity constraints, which are policy-driven. Besides, warehouses are important buffers to translate uncertainty from upstream stages into a downstream commitment, and last-mile delivery is most vulnerable to delays propagating from upstream stages. These observations go towards justifying not only the importance of characterizing ETA in terms of a stage-wise duration distribution rather than analyzing ETA as a point estimate but also stage-wise bottleneck analysis in terms of mitigation strategies related to berth allocation, inspection prioritization, rebalancing and dynamic routing. The study brings about the needed connection between analytics and decision-making by suggesting an integrated KPI framework in the areas of time, reliability, cost, risk, and carbon. The framework helps fight against negative effects associated with a lack of operational resilience; at the same time, it makes manufacturing sustainable. Although there were limitations, the results contribute to building the required roadmap in both the academic and practical worlds. Finally, it would appear that the foregoing analysis of end-to-end logistics analytics positions it squarely in the realm of a socio-technical system, where the shape of the data, modeling, governance, and decision rights are inextricably linked. The focus of research in the future regarding the above-mentioned end-to-end logistics network analysis will need to focus on empirical datasets with more than one nodal point, careful assessment of performance in the face of leakage, and a more integrated approach to modeling the carbon and policy aspects of predictive and prescriptive analysis.

REFERENCES

[1] Chaffin, C., et al. (2024). Systematic review of supply chain control tower critical success factors. Operations and Supply Chain Management, 17(3).

[2] DCSA. (2020). DCSA industry blueprint: Track and trace standards and interfaces (Version 1.0). Digital Container Shipping Association.

[3] Gabellini, M., Civolani, L., Calabrese, F., & Bortolini, M. (2024). A deep learning approach to predict supply chain delivery delay risk based on macroeconomic indicators: A case study in the automotive sector. Applied Sciences, 14(11), 4688. https://doi.org/10.3390/app14114688

[4] Gunasekaran, A., et al. (2025). An interpretive analysis of influential drivers for supply chain control towers. (ScienceDirect record).

[5] Hofman, W., Migeotte, J., Labare, M. L. M., Rukanova, B. D., & Tan, Y. (2021). Using business data in customs risk management: Data

quality and data value perspective. In Electronic Government (EGOV 2021) (LNCS 12850). Springer. https://doi.org/10.1007/978-3-030-84789-0_20

[6] IAPH. (2024). Just-in-time arrival implementation and port call optimization: Lessons and recommendations. International Association of Ports and Harbors.

[7] IMO. (2023). Guidelines for harmonization and improved coordination of port calls. IMO Facilitation Committee (FAL).

[8] Karklina-Admine, I., et al. (2024). Data-driven customs risk management. World Customs Journal.

[9] Kumbhar, M., Ng, A., & Bandaru, S. (2023). A digital twin based framework for detection, diagnosis, and improvement of throughput bottlenecks. Journal of Manufacturing Systems, 68, 1–17. https://doi.org/10.1016/j.jmsy.2022.11.015

[10] Maritime Policy & Management. (2022). A deep learning approach for port congestion estimation and prediction using AIS-derived measures. Maritime Policy & Management.

[11] Mo, B., Wang, Q. Y., Guo, X., Winkenbach, M., & Zhao, J. (2023). Predicting drivers' route trajectories in last-mile delivery using a pair-wise attention-based pointer neural network. arXiv:2301.03802.

[12] Müller, C., et al. (2025). Predictive methods for delivery delays in supply chain and logistics: A systematic literature review. (Preprint record).

[13] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71

[14] Ragazzini, L., et al. (2024). Digital twin-based bottleneck prediction for improved system performance. Computers in Industry.

[15] Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., & Koffel, J. B. (2021). PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. Journal of the Medical Library Association, 109(2), 174–200. https://doi.org/10.5195/jmla.2021.962

[16] Saber, S. M., Thowai, K. Z., Rahman, M. A., Hassan, M. M., Bari, A. B. M. M., & Raihan, A. (2025). High-accuracy prediction of vessels' estimated time of arrival in seaports: A hybrid machine learning approach. Maritime Transport Research, 100133. https://doi.org/10.1016/j.martra.2025.100133

[17] Štepec, D., Grasso, M., & Cazzanti, L. (2020). Port turnaround time prediction using machine learning. (IEEE conference paper record).

[18] Su, M., et al. (2025). Port congestion and container freight rate dynamics. Frontiers in Marine Science, 12.

[19] UNCTAD. (2020). Review of Maritime Transport 2020: Shipping in times of the COVID-19 pandemic. United Nations Conference on Trade and Development.

[20] Vijayakumar, S. (2025). Technology-centric and data-driven customs risk management for supply chain security. World Customs Journal.

[21] Wu, L., Wen, H., Hu, H., Mao, X., Xia, Y., Shan, E., Zheng, J., Lou, J., Liang, Y., Yang, L., Zimmermann, R., Lin, Y., & Wan, H. (2023). LaDe: The first comprehensive last-mile delivery dataset from industry. arXiv:2306.10675.

[22] World Economic Forum. (2020). Mapping TradeTech: Trade in the fourth industrial revolution. World Economic Forum.

[23] International Monetary Fund. (2022). Customs matters: Strengthening customs administration in a changing world. International Monetary Fund.

[24] World Customs Organization. (2020). SAFE framework of standards to secure and facilitate global trade. World Customs Organization.

[25] World Trade Organization. (2023). Trade Facilitation Agreement database. World Trade Organization.

[26] PRISMA Statement Group. (2021). PRISMA 2020 statement resources (checklists and flow diagrams). prisma-statement.org.

[27] Frontiers in Marine Science. (2025). Port congestion and freight rate dynamics—open access article record. Frontiers.

[28] UNCTAD. (2020). Review of Maritime Transport 2020 (full report PDF). UNCTAD.

[29] DCSA. (2020). Track & trace standard interfaces (reference implementation notes). DCSA.