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Petri Net Applications in Logistics: A Comprehensive Review[1]

Lojistikte Petri Net Uygulamaları: Kapsamlı Bir İnceleme

Mohsen EBADOLLAHIKALKHORAN
MSc Candidate, Istanbul Ticaret University, Instıtute of Graduate Education,
ebadollahi_mohsen@yahoo.com
https://orcid.org/0009-0000-9400-6371

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Vahideh ASADOLLAHI
MSc Candidate, Istanbul Ticaret University, Instıtute of Graduate Education
asadollahi.vahideh@gmail.com
https://orcid.org/0009-0006-1996-707X

Pınar GÜROL
Asst. Prof. Dr., Piri Reis University, Faculty of Economics and Administrative Sciences,
Logistics Management, pinargurol@gmail.com
https://orcid.org/0000-0001-7368-1757

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ÖZET

Lojistik sistemleri, küreselleşme, e-ticaret ve sürdürülebilir ile dayanıklı operasyonlara duyulan artan ihtiyaç nedeniyle giderek daha karmaşık hâle gelmektedir. Ayrık olaylı dinamik sistemler için biçimsel bir modelleme aracı olan Petri Net'ler, lojistik süreçlerde eşzamanlılık, belirsizlik ve kaynak paylaşımını temsil etmek için güçlü bir yöntem sunmaktadır. Bu çalışma, Petri Net uygulamalarına ilişkin yapısal bir derleme sunmaktadır. Bulgular, Zamanlı ve Stokastik Petri Net'lerin ulaşım ve çizelgeleme problemlerinde yaygın olarak kullanıldığını; Renklendirilmiş Petri Net'lerin özellikle depolama ve çok ürünlü sistemlerde etkili olduğunu; hibrit Petri Net yaklaşımlarının ise limanlar ve akıllı terminallerde ortaya çıktığını göstermektedir. Petri Net tabanlı modeller, karmaşık süreçlerin tanımlanması ve alternatif politikaların değerlendirilmesinde güçlü bir destek sağlasa da ölçeklenebilirlik ve gerçek zamanlı verilerle entegrasyon gibi zorluklarla karşı karşıyadır. Derleme, sınırlı alanlar arası karşılaştırmalar, dijital ikiz ve veri odaklı yaklaşımların yetersiz kullanımı ve makine öğrenmesinin Petri Net tabanlı karar destek sistemlerine yeni fakat umut vadeden entegrasyonu gibi araştırma boşluklarını belirlemektedir. Genel olarak çalışma, Petri Net'lerin lojistikte nasıl kullanıldığına ilişkin bütüncül bir bakış sunmakta ve siber-fiziksel entegrasyon, sürdürülebilirlik ve akıllı karar destek mekanizmalarına yönelik gelecek araştırma yönlerini ortaya koymaktadır

Keywords:

Petri Nets,

Logistics Systems,

Supply Chain Management,

ABSTRACT

Logistics systems are becoming increasingly complex due to globalization, e-commerce, and the growing need for sustainable and resilient operations. Petri Nets (PNs), as a formal modeling tool for discrete-event dynamic systems, offer a powerful way to represent concurrency, uncertainty, and resource sharing in logistics processes. This paper presents a structured narrative review of PN applications in logistics. The results show that Timed and Stochastic PNs are widely used in transportation and scheduling problems; Colored PNs are especially effective for warehousing and multi-product systems; and hybrid PN approaches are emerging in port logistics and smart terminals. PN-based models provide strong support for describing complex processes and evaluating alternative policies, but they also face challenges related to scalability and integration with real-time data. The review identifies research gaps, including limited cross-domain comparisons, limited use of digital-twin and data-driven approaches, and an early but promising role for machine learning in PN-based decision support. Overall, the paper offers a consolidated view of how PNs are used in logistics and outlines promising research directions related to cyber-physical integration, sustainability, and intelligent decision support.

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1. INTRODUCTION

Logistics plays a central role in global economic development by ensuring the continuous movement of materials, products, information, and financial resources across geographically dispersed networks. Effective logistics operations enable firms to respond rapidly to changing demand, control operational costs, and maintain competitiveness in increasingly dynamic markets (Christopher, 2023; Ghiani et al., 2004). At the national and international levels, logistics performance is directly linked to economic growth and competitiveness, a relationship reflected in indicators such as the World Bank's Logistics Performance Index. Countries with well-developed logistics infrastructures consistently attract more investment, support higher export capacities, and generate greater employment opportunities (Lau and Lee, 2000; Meixell and Norbis, 2008).

In recent years, globalization, digital transformation, and the rise of e-commerce have reshaped logistics systems. Modern supply chains span multiple continents and involve numerous stakeholders who must coordinate seamlessly across time and space. The rise of e-commerce has intensified the need for fast, reliable, and customer-oriented delivery services, as well as real-time visibility, integrated information flows, and synchronized decision-making (Hosseini et al., 2019). At the same time, sustainability and resilience have become critical priorities. Firms face growing pressure to reduce environmental impact, adopt circular economy principles, and remain robust against disruptions such as pandemics, natural disasters, and geopolitical instability (Ivanov et al., 2019; Queiroz et al., 2022).

Logistics systems are widely recognized as complex socio-technical structures characterized by uncertainty, interdependence, and dynamic interactions between multiple actors, processes, and technologies (Giannopoulos, 2004). Traditional analytical techniques often fall short in capturing this complexity, especially in systems defined by concurrent activities, stochastic variations, and resource constraints. These challenges create a strong need for advanced modeling and simulation tools capable of representing the dynamic behavior of logistics operations and evaluating alternative policies under controlled conditions.

Petri Nets (PNs)offer a robust graphical and mathematical formalism for modeling discrete-event dynamic systems and have proven especially suitable for representing concurrency, synchronization, and resource sharing (Murata, 1989). Over the years, numerous extensions such as Timed Petri Nets, Colored Petri Nets, Stochastic Petri Nets, and Hybrid PNs have been developed to better reflect real-world logistics environments. These formalisms allow analysts to incorporate time delays, probabilistic behaviors, heterogeneous product flows, and interactions between discrete and continuous processes (Ramchandani, 1974; Jensen and Kristensen, 2009; David and Alla, 2010). As a result, PNs support both qualitative analysis (such as deadlock detection or liveness) and quantitative evaluation of key performance metrics, including throughput, waiting times, and reliability.

Despite the broad applicability of Petri Nets, the literature on their use in logistics remains fragmented. Earlier reviews concentrated primarily on supply chain management (Zhang et al., 2010) or specific sectors such as green logistics or intelligent transportation. Few studies conduct comprehensive cross-domain comparisons or evaluate how different PN formalisms perform across diverse logistics contexts. Additionally, limited attention has been given to the relationship between PN applications and emerging technological paradigms such as digital twins, Industry 4.0 architectures, AI-driven decision-making, and sustainability frameworks (Tiwari et al., 2021). This gap restricts researchers' and practitioners' ability to see the broader landscape and select appropriate PN approaches for new or complex logistics problems.

The aim of this paper is to provide a structured and integrative overview of PN applications in logistics. The review identifies the logistics domains where PNs have been used including supply chains and production systems, transportation, warehousing, and port operations, and classifies the various PN formalisms applied in these areas. It synthesizes the main objectives and performance measures observed in the literature, connects PN research with current technological trends such as digital twins and AI-based optimization, and highlights key research gaps and future directions. The paper proceeds by presenting the theoretical foundations of logistics systems and Petri Nets, followed by an analysis of applications across logistics domains, a comparative cross-domain synthesis, and a discussion of emerging research opportunities.

2. APPLICATIONS OF PETRI NETS IN LOGISTICS

2.1. Supply Chain and Production Systems

Supply chain and production environments are characterized by continuous flows of materials, information, and decision processes that unfold across multiple stages. These systems typically involve parallel activities, variable lead times, and interdependencies that create complex behavioral dynamics. PNs have increasingly been used to describe these interactions because their formal structure enables analysts to map resource constraints, synchronization points, and process logic with high precision. In green and circular supply chain contexts, recent studies demonstrate how Colored PNs can model forward and reverse flows simultaneously, providing an integrated view of production, distribution, and recovery activities. The work of Kaiyandra et al. (2024), for instance, shows that Colored PNs can capture environmental trade-offs, stakeholder interactions, and product differentiation within multi-stage systems, making them highly suitable for sustainability-driven supply chain analysis. Similar modeling advantages appear in IoT-supported supply networks, where PNs help formalize how sensor-driven data streams interact with logistics events such as tracking, verification, and coordination (Balamurugan et al., 2021).

In production systems, Stochastic PNs and their extensions have gained traction as tools for analyzing uncertainty, variable processing times, and system responsiveness. Mesmia and Barkaoui (2024) introduce Learning Flow Stochastic PNs, which combine probabilistic timing with adaptive agent behavior to reflect how real production lines evolve under changing operational conditions. These models are particularly useful in evaluating performance criteria such as throughput, reliability, and delay propagation in manufacturing environments exposed to disruptions or fluctuating workloads. At the same time, literature also emphasizes the methodological challenges associated with modeling large production systems. Grobelna and Karatkevich (2021) highlight the persistence of state-space explosion and the growing need for PN-based frameworks that integrate seamlessly with Industry 4.0 technologies, especially in settings where automation, cyber–physical systems, and real-time data streams play a central role. Altogether, existing research confirms that PNs remain one of the most effective tools for representing the structural and stochastic complexity of supply chains and production systems, enabling more accurate simulation and more informed decision-making.

2.2. Transportation Systems

Transportation systems constitute one of the most prominent application areas of PNs in logistics, particularly for problems involving routing, scheduling, and real-time traffic management. At the operational level, PNs provide a natural way to describe vehicle movements, conflict points, and resource-sharing in road, rail, and internal transport networks. For instance, Zhang et al. (2021) model a multi automatic guided vehicle system as a place-timed PN and then embed this model into a deep reinforcement learning framework to jointly address dispatching and path planning. The PN structure captures collision and deadlock risks through explicit control places and transitions, while the learning component searches for efficient routing policies under these structural constraints. This combination demonstrates how Timed PNs can move beyond static analysis to support adaptive, data-driven control of automated transport in environments such as unmanned warehouses and automated port terminals. Similarly, in urban road networks, Colored PNs have been used as the underlying formalism in Intelligent Transportation Systems that must react to rapidly changing conditions. Brazález et al. (2022), for example, propose a pandemic-oriented ITS in which complex event processing and fuzzy logic evaluate health and mobility indicators, while Colored PNs encode restricted and unrestricted areas and compute fast routes that respect dynamic mobility constraints.

Beyond local traffic management, PNs are increasingly used to analyze transport systems at the level of international and regional corridors, with a growing emphasis on sustainability. Kabashkin and Sansyzbayeva (2024) develop a methodological framework based on Evaluation PNs (E-Nets) to model sustainable transport corridors, integrating environmental, social, and economic indicators into a unified simulation tool. Their approach shows how PN-based models can represent multimodal flows, capacity restrictions, and policy scenarios while simultaneously tracking key sustainability metrics such as emissions, service quality, and resilience under different operating conditions. In this way, PNs serve as a bridge between micro-level control and macro-level planning, supporting both detailed operational decision-making and strategic evaluation of transport policies. Together, these studies illustrate that PN formalisms offer a versatile toolkit for transportation modeling, capable of capturing both the discrete-event dynamics of traffic and the broader performance and sustainability objectives of logistics networks.

2. 3. Warehousing and Inventory Management

Warehousing operations constitute a critical link between upstream supply and downstream distribution activities, and their complexity has increased with growing product variety, faster order cycles, and automation demands. PNs offer a natural modeling framework for warehouse environments because they can capture sequencing constraints, resource competition, and the concurrency typical of storage, retrieval, sorting, and palletizing processes. For instance, Iskandar et al. (2023) demonstrate how Petri Net-based modeling facilitates the design and control of automated intralogistics systems involving sorters, palletizers, conveyors, and stacker cranes, enabling a structured transformation of PN models into PLC ladder logic and validating system behavior in a virtual plant simulation environment. Similarly, Mahjoub et al. (2021) incorporate Timed Coloured PNs into a broader logistic network framework to represent warehouse storage delays, vehicle flows, and temporal constraints, showing that PN formalisms can integrate storage dynamics with transportation and replenishment processes in a mathematically rigorous way. These studies highlight the suitability of PN models for analyzing performance metrics such as cycle time, handling capacity, and the responsiveness of automated material-handling systems within modern warehousing operations.

Beyond conventional warehouse layouts, advanced systems such as puzzle-based storage have also benefited from PN-driven modeling. Puzzle-based storage architectures seek to maximize storage density by enabling racks or loads to move within compact grid structures, creating a tightly constrained environment in which simultaneous moves, conflicts, and reconfiguration issues significantly affect performance. Weerasinghe et al. (2023) introduce modular PNs to analyze PBS systems, demonstrating how modular PN structures can manage the combinatorial complexity of multi-load, multi-escort, and multi-directional motions, while enabling verification of critical system properties such as reachability, deadlock-freeness, and liveness. Complementing these contributions, Kaiyandra et al. (2023) note that inventory-related processes are increasingly modeled through Colored or Timed PNs to evaluate system performance and identify inefficiencies in discrete-event warehouse operations. Collectively, this body of work shows that Petri Nets, especially modular, colored, and timed extensions, represent a powerful analytical toolset for describing the operational logic, capacity constraints, and dynamic interactions that shape both traditional and high-density automated warehousing systems.

2.4. Port and Terminal Operations

Port and terminal operations involve highly synchronized processes in which quay cranes, yard cranes, automated guided vehicles, and internal transport equipment interact within spatially constrained environments. PNs offer a robust modeling structure for capturing these concurrent flows, resource-sharing conflicts, and potential deadlock situations that arise in terminal traffic systems. Wu et al. (2022) demonstrate that PN based control can effectively detect and resolve deadlocks among interacting port and terminal operations involve highly synchronized processes in which quay cranes, yard cranes, automated guided vehicles, and internal transport equipment interact within spatially constrained environments. PNs offer a robust modeling structure for capturing these concurrent flows, resource-sharing conflicts, and potential deadlock situations that arise in terminal traffic systems.

Wu et al. (2022) demonstrate that PN based control can effectively detect and resolve deadlocks among interacting automated guided vehicles, capturing blocking states, collision risks, and coordinated vehicle movements through formal PN structures. High-level PN models have similarly been applied to autonomous navigation in container terminals, enabling verification of movement rules, obstacle-avoidance logic, and synchronized decision-making across multiple autonomous vehicles (Kadri et al., 2022). These applications highlight the suitability of PN formalisms for representing the structural and behavioral complexity of automated terminal operations.

Beyond internal traffic control, Petri Nets also contribute to higher-level planning and performance analysis in intermodal and maritime terminals. Fallah et al. (2025) employ Timed Colored PNs integrated with fuzzy data to model terminal planning scenarios, addressing uncertainties in vessel arrival times, handling durations, and yard capacity constraints. Their approach enables terminal operators to assess alternative planning strategies and predict bottlenecks under variable operational conditions. In addition, Du et al. (2023) develop an in-the-loop testing platform for yard space allocation that incorporates PN logic to validate container storage strategies and real-time reconfiguration decisions. Complementing these studies, Jalal et al. (2023) use Stochastic PNs to estimate the operational performance and reliability of quay cranes, showing that PN repair cycles, downtime behavior, and the associated impacts on terminal throughput. Together, these contributions demonstrate that Petri Nets provide a comprehensive analytical framework for both operational control and strategic planning in modern port and terminal environments. High-level PN models have similarly been applied to autonomous navigation in container terminals, enabling verification of movement rules, obstacle-avoidance logic, and synchronized decision-making across multiple autonomous vehicles (Kadri et al., 2022). These applications highlight the suitability of PN formalisms for representing the structural and behavioral complexity of automated terminal operations.

3. CROSS-DOMAIN SYNTHESIS

A synthesis of the reviewed studies demonstrates that PNs have become a unifying analytical framework across distinct logistics domains, despite the varied operational demands of supply chains, transportation systems, warehousing environments, and port terminals. Each domain involves concurrent processes, resource contention, and event-driven system behavior, which align naturally with the structural and mathematical characteristics of PNs. In supply chain and production systems, Colored and stochastic PN extensions have been particularly effective in representing product differentiation, sustainability-driven flows, and probabilistic processing behaviors (Kaiyandra et al., 2024; Mesmia and Barkaoui, 2024). These models capture both synchronized production sequences and variable operational conditions, enabling analysts to evaluate performance metrics such as throughput, reliability, and environmental impact in multi-stage processes. The presence of IoT-enabled monitoring in modern supply networks has further expanded the applicability of PNs by allowing formal representation of sensor-driven events and information flows (Balamurugan et al., 2021).

A similar alignment appears in transportation systems, where routing, scheduling, and conflict management depend heavily on temporal coordination. Timed and Colored PNs offer a structured means of representing vehicle interactions, access conflicts, and real-time decision rules in automated guided vehicles systems, urban road networks, and multimodal corridors (Zhang et al., 2021; Brazález et al., 2022). By embedding PN models within learning or fuzzy frameworks, recent research demonstrates that transport systems can adaptively respond to congestion, public health constraints, and operational variability. At the strategic level, Evaluation PNs have shown promise in analyzing international transport corridors where sustainability indicators must be considered simultaneously (Kabashkin and Sansyzbayeva, 2024). Across these studies, PNs serve to bridge micro-level operational control with macro-level transport planning.

Warehousing and inventory systems further illustrate the versatility of PN formalisms. Because warehouse operations involve dense interactions among storage, retrieval, sorting, and replenishment processes, PN-based models are well suited to capture concurrency and sequencing constraints. Timed and Colored PNs have proven useful in representing automated intralogistics systems, integrating delays, vehicle motions, and capacity limitations in distribution centers (Iskandar et al., 2023; Mahjoub et al., 2021). Meanwhile, innovative configurations such as puzzle-based storage systems rely on modular PNs to manage the combinatorial complexity of multi-load and multi-directional movements within compact grid structures (Weerasinghe et al., 2023). These approaches highlight PNs' ability to maintain analytical clarity even in highly constrained, automation-intensive environments.

Port and terminal operations combine many of the complexities seen in other logistics domains; tight timing constraints, heterogeneous equipment interactions, uncertainty in arrival patterns, and spatial limitations. Here, PNs support both operational control and high-level planning. Deadlock detection among automated guided vehicles, autonomous navigation rules, and container-handling interactions can be formalized through high-level and timed PN variants (Wu et al., 2022; Kadri et al., 2022). At the same time, stochastic and timed Colored PNs contribute to performance evaluation by modeling crane reliability, yard capacity, vessel arrival variability, and reconfiguration decisions (Fallah et al., 2025; Du et al., 2023; Jalal et al., 2023). These strategies allow terminal operators to simulate alternative resource allocations, anticipate congestion, and maintain service reliability in increasingly automated port environments.

Taken together, the cross-domain evidence confirms that PNs provide a coherent methodological foundation capable of capturing the structural, temporal, and stochastic dimensions of logistics systems. While each domain adopts specific PN extensions tailored to its operational characteristics: Colored PNs in warehouses and green supply chains, Timed PNs in transportation systems, modular PNs in puzzle-based storage, and Stochastic PNs in port reliability assessment, the underlying formal principles remain consistent. This makes PNs uniquely positioned as a unifying analytical tool for logistics, offering both domain-specific precision and cross-domain comparability. As logistics systems become more automated, data-driven, and sustainability-oriented, the integrative modeling capabilities of PNs are likely to gain even greater importance.

4. DISCUSSION AND CONCLUSION

The collective findings of this review demonstrate that PNs have become a foundational and integrative modeling paradigm for analyzing logistics systems that are increasingly complex, automated, and data-intensive. Across diverse logistics domains PNs consistently prove capable of representing concurrency, synchronization, uncertainty, and resource contention, all of which are essential characteristics of contemporary logistics processes. The comparative evidence across the literature shows that each PN extension contributes domain-specific analytical value: Colored PNs excel in capturing product heterogeneity and environmentally oriented supply chain dynamics (Kaiyandra et al., 2024), Stochastic PNs effectively model uncertainties, variable processing times, and reliability aspects in production lines and maritime terminals (Mesmia and Barkaoui, 2024; Jalal et al., 2023), while Timed and Timed-Colored PNs are particularly suited to transportation systems and port activities characterized by strict temporal constraints and coordinated dispatching (Zhang et al., 2021; Fallah et al., 2025). These variations reflect not only the versatility of PN formalisms but also their capacity to deliver coherent insights across domains without sacrificing methodological rigor.

A key conclusion emerging from existing studies is that Petri Nets increasingly function not only as descriptive modeling tools but also as practical decision-support instruments in technology-driven logistics environments. Their integration with reinforcement learning, complex event processing, fuzzy logic, and IoT-based monitoring illustrates a shift toward hybrid modeling approaches that merge the structural precision of PNs with adaptive, data-driven decision-making (Brazález et al., 2022; Balamurugan et al., 2021). In warehousing and intralogistics, PN based models have enabled the design, verification, and virtual commissioning of automated systems incorporating conveyors, automated storage and retrieval systems, and palletizers, allowing engineers to test operational logic prior to physical deployment (Iskandar et al., 2023). Similarly, in ports and container terminals, high-level PN models have supported autonomous navigation and the coordinated movement of automated guided vehicles by encoding obstacle-avoidance constraints, shared-resource logic, and synchronized motion policies that prevent deadlocks and collisions (Kadri et al., 2022). Such applications confirm that PNs now operate as active components of real-time and simulation-based logistics management, supporting both tactical and strategic system design decisions.

Despite their demonstrated strengths, several methodological challenges limit the full scalability and integration of PN based approaches across logistics domains. Foremost among these is the issue of state-space explosion, which remains difficult to overcome in large systems that combine timing, stochasticity, heterogeneity, and multi-agent interactions (Grobelna and Karatkevich, 2021). Although modular, hierarchical, and colored PN variants alleviate the issue to a degree, the computational demands associated with Industry 4.0 logistics underscore the need for more scalable PN modeling techniques. Another challenge concerns the incomplete integration of PNs with data-driven optimization, predictive analytics, and machine learning.

Looking forward, several future research paths appear particularly promising for advancing the value of PN based modeling in logistics. One important trajectory involves enhancing the interoperability of PNs with real-time data infrastructures, AI-enabled control architectures, and Digital Twin platforms, enabling PN models to adapt dynamically based on streaming data and thereby support predictive maintenance, adaptive routing, and real-time system reconfiguration (Du et al., 2023; Kadri et al., 2022). Another direction concerns improving scalability through hybrid modeling techniques that combine formal PN structures with decomposition heuristics, surrogate simulation models, distributed computation, or machine learning-assisted state-space reduction. The growing emphasis on sustainability across global logistics further highlights the need for PN based tools capable of evaluating environmental, economic, and social performance indicators concurrently, thereby supporting multi-criteria assessments of green logistics policies, sustainable transport corridors, and energy-efficient warehouse and terminal operations (Kabashkin and Sansyzbayeva, 2024). Additionally, integrating reinforcement learning and multi-agent coordination into PN frameworks presents opportunities for developing adaptive, autonomous logistics models capable of responding to disruptions and evolving operational environments without manual intervention.

In conclusion, PNs provide a robust, extensible, and methodologically coherent foundation for analyzing logistics systems undergoing rapid digitalization and structural transformation. Their dual capability to integrate qualitative behavioral analysis with quantitative performance evaluation makes them uniquely suited for capturing the dynamic interactions that shape supply chains, transportation systems, warehouses, and port terminals. As global logistics continues to evolve in response to technological innovation, sustainability pressures, and increasing operational uncertainty, the adaptability of PNs positions them as a crucial tool for both academic researchers and industry practitioners seeking to design resilient, efficient, and intelligent logistics systems. Continued methodological innovation and deeper integration with real-time data analytics, optimization methods, and autonomous control technologies will further enhance the capacity of Petri Nets to support strategic planning and operational decision-making across the logistics spectrum.

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