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FROM SIMULATION TO STRATEGY: DISCRETE-EVENT APPROACHES TO PRIME MOVER ALLOCATION IN CONTAINER TERMINALS

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Abstract:

The increasing complexity of container terminal operations has amplified the challenges associated with the efficient allocation of prime movers, which serve as the vital transport link between quay cranes and yard cranes. Inefficient allocation can lead to congestion, prolonged vessel turnaround times, and higher operational costs, ultimately undermining port competitiveness. Addressing this challenge requires robust analytical frameworks capable of capturing the dynamic, stochastic, and interdependent nature of container terminal systems. This study aims to examine how discrete-event simulation (DES) and related analytical approaches have been applied to optimize prime mover allocation in container terminals. By utilizing Scopus AI analytics, the study conducted a structured review based on a comprehensive search string that integrated key concepts of simulation, resource allocation, optimization, and efficiency in port logistics. The search produced a systematically organized corpus of scholarly works, encompassing journal articles, conference proceedings, and technical reports published between 2000 and 2025. The analysis was guided by Scopus AI features

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including the *Summary, Expanded Summary, Concept Maps, Topic Experts, and Emerging Themes*, allowing for both bibliometric mapping and narrative synthesis of the research landscape. The findings highlight three major contributions of DES to prime mover allocation: (i) operational optimization through simulation-based frameworks that reduce congestion and improve quay crane productivity, (ii) strategic planning via predictive simulation models and integrated scheduling, and (iii) sustainability-focused approaches that minimize fuel consumption and emissions. Emerging themes such as machine learning enhanced DES, decision support systems, and Boolean-algebraic methods underscore the evolution of research toward intelligent and adaptive allocation strategies. The study advances theory by framing prime mover allocation as both an operational and strategic systems problem, while offering practical insights for improving terminal efficiency, resilience, and sustainability. Limitations include dataset scope and limited empirical validation, with future research needed on predictive simulation, digital twin integration, and comprehensive sustainability metrics.

Keywords:

Prime Mover Allocation, Discrete-Event Simulation, Container Terminal Operations, Optimization and Scheduling & Port Efficiency and Sustainability

Introduction

The continuous growth of global trade has heightened demand for efficient container terminal operations, positioning ports as critical nodes in international supply chains. Terminals act as the interface between maritime and land transport, where the allocation of quay cranes (QCs), yard cranes (YCs), and prime movers (PMs) determines productivity and competitiveness (Wanigasekara & Torres, 2024). PMs serve as the essential transport link between quay and yard operations, directly influencing vessel turnaround time, congestion, and service reliability (Yu et al., 2018). However, the increasing scale of vessels, dynamic container flows, and fluctuating demand make PM allocation a complex operational challenge, often leading to bottlenecks and underutilization of resources (Dulebenets, 2017).

Past studies have applied diverse analytical and simulation-based methods to address terminal inefficiencies, with discrete-event simulation (DES) emerging as the dominant approach. DES captures system variability, models subsystem interdependencies, and tests allocation strategies under varying scenarios (Zhou et al., 2021; Schwientek et al., 2020). Applications include optimizing yard allocation (Zhou et al., 2021), analyzing the impact of container dispersion on QC productivity (Yu et al., 2018), predicting operation times using predictive DES with machine learning (Park et al., 2024), and supporting terminal expansion planning (Ambrosino & Tànfani, 2009; Loke et al., 2015). Despite these contributions, most studies remain fragmented, addressing isolated operational issues such as yard allocation or crane scheduling rather than offering a consolidated view of DES applications to prime mover allocation (Ursavas, 2022).

This gap highlights the importance of synthesizing DES applications to PM allocation across operational, strategic, and sustainability dimensions. While simulation optimization frameworks and decision support systems (DSS) have advanced planning (Ursavas, 2022; Liu & Wang, 2005), less attention has been given to predictive DES, sustainability-oriented modeling, and hybrid optimization. Furthermore, despite the rising importance of green port initiatives, relatively few studies link PM allocation to environmental outcomes such as fuel consumption and carbon emissions (Di Vaio et al., 2021). Accordingly, this study analyzes the field's evolution, maps conceptual linkages, and identifies future research opportunities.

This review aims to (i) analyze the breadth of DES applications to prime mover allocation, (ii) construct a concept map linking efficiency, strategy, and sustainability, (iii) identify key topic experts and influential studies, and (iv) highlight emerging themes. Unlike prior studies, this review integrates operational and strategic perspectives, offering insights for both theory and practice. It shows how DES can reduce congestion, optimize resource use, and support green port initiatives. The remainder of this paper outlines the methodology in Section 2, results and discussion in Section 3, and concludes with key findings, implications, and future directions in Section 4.

Methodology

This study employed a systematic review approach supported by Scopus AI analytics to investigate advances in prime mover allocation within port operations through DES. Scopus was selected as the core database because of its extensive coverage of peer-reviewed journals, conference proceedings, and industry-relevant publications across engineering, logistics, and operational research disciplines.

To capture the breadth of studies related to resource allocation and DES in port operations, the following search string was used:

("discrete-event" OR "event-driven" OR "stochastic" OR "simulation") AND ("prime mover" OR "equipment" OR "vehicle" OR "resource") AND ("allocation" OR "assignment" OR "distribution" OR "management") AND ("container terminal" OR "port" OR "shipping" OR "logistics") AND ("efficiency" OR "optimization" OR "performance" OR "utilization")

This search string was designed to maximize inclusivity while ensuring relevance to resource allocation, simulation methodologies, and container terminal performance. The search returned a structured corpus of studies across journals, conference proceedings, and technical reports from 2000 to 2025, reflecting historical development and current research frontiers.

The review leveraged five core features of Scopus AI to structure the analysis as shown in Figure 1. The Summary function provided a consolidated overview of the key findings across the retrieved literature, capturing dominant methodologies such as DES and simulation optimization and research contexts including container terminals and shipping logistics. It also synthesized the primary evaluation criteria employed in the field, such as efficiency, performance, and utilization. This step ensured a clear baseline understanding of how DES has evolved in the study of port operations.

Building on this foundation, the Expanded Summary offered a more detailed thematic breakdown, drawing attention to specialized subtopics and applications. For example, previous research addressed yard allocation strategies (Zhou et al., 2021), the impact of container location dispersion on QC productivity (Yu et al., 2018), predictive discrete-event models (Park et al., 2024), and sustainable prime mover deployment (Loke et al., 2015). This expanded synthesis was instrumental in mapping methodological diversity while also revealing interdisciplinary connections within the literature.

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The Concept Map feature, automatically generated by Scopus AI, further enhanced understanding of the research landscape. This visualization highlighted interconnections between DES, prime mover allocation, optimization, sustainability, and strategic planning. It also revealed significant clusters of research such as simulation optimization hybrids (Ursavas, 2022), predictive analytics (Park et al., 2024), and environmentally oriented studies (Abu-Aisha et al., 2021). These clusters collectively illustrated how the field has shifted from focusing solely on operational models to adopting more integrated strategic frameworks.

The identification of Topic Experts was another crucial component of the framework. By analyzing citation networks and publication productivity, Scopus AI highlighted the leading authors and institutions shaping this domain. Among the most influential contributors were Zhou et al. (2021), whose work on simulation optimization remains widely cited; Ambrosino and Tànfani (2009), who advanced research in container terminal expansion planning; and Jahn and colleagues (Schwientek et al., 2020), who provided significant insights into dispatching strategies. These scholars are intellectual anchors in the field, contributing methodological and applied advancements.

Finally, Scopus AI revealed Emerging Themes shaping the future trajectory of research. Key trends include the integration of machine learning with DES to enable predictive terminal operations (Park et al., 2024), the use of sustainability metrics and carbon footprint reduction in evaluating terminal performance (Abu-Aisha et al., 2021), and the development of decision support systems for dynamic resource allocation (Ursavas, 2022). Collectively, these emerging directions demonstrate a growing emphasis on balancing operational efficiency with environmental sustainability and strategic imperatives.

Aligned with the overarching aim of this study to analyze the research landscape through Scopus-AI analytics, this methodological framework provides an in-depth exploration of the conceptual development of DES in prime mover allocation. It identifies recognized topic experts, uncovers thematic linkages, and highlights emerging areas of inquiry within the field. By employing bibliometric mapping and narrative synthesis, this review not only situates existing contributions but also guides scholars and practitioners seeking to advance future research that integrates efficiency, resilience, and sustainability in container terminal options.

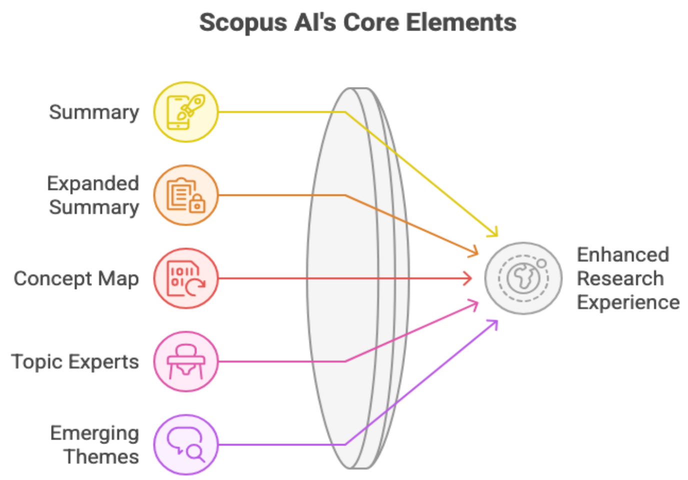

Figure 1: 5 Core Elements of Scopus AI

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Result and Discussion

The findings of this review are presented through a structured synthesis derived from the Scopus AI analytical outputs, namely the *Summary and Expanded Summary*, the *Concept Map*, and the identification of *Topic Experts and Emerging Themes*. Together, these dimensions provide a comprehensive understanding of how DES has been applied to prime mover allocation in container terminals and how the research landscape has evolved.

Summary and Expanded Summary

The Summary and Expanded Summary revealed that DES has consistently been positioned as a pivotal methodology for addressing operational complexities in container terminals. While earlier studies concentrated on simulation-based assessments of yard allocation and resource utilization (Zhou et al., 2021; Yu et al., 2018), more recent contributions have expanded toward predictive modeling and sustainability-oriented strategies (Park et al., 2024; Loke et al., 2015). This progression underscores the methodological diversification of DES, where traditional operational models are increasingly complemented by hybrid optimization, machine learning integration, and scenario-based analysis.

The synthesis of the Summary and Expanded Summary findings demonstrates that DES has emerged as a dominant methodological approach in addressing the complexities of prime mover allocation in container terminals. Across the literature, DES has been applied to evaluate operational efficiency and support strategic decision-making in terminal expansion, sustainability, and technological innovation. The results highlight the challenges of prime mover allocation, the advantages of simulation-based solutions, and the evolution of industry practices toward more adaptive and sustainable models.

One of the most consistent findings is the ability of DES models to simulate intricate operational processes such as vessel berthing, container loading and unloading, and traffic management of prime movers within the terminal. Studies integrating yard allocation with vehicle congestion demonstrated that simulation-based optimization can iteratively improve resource allocation and reduce overall traffic time (Zhou et al., 2021). Similarly, research on the dispersion of container locations confirmed that DES can capture the impact of storage patterns on QC performance, underscoring the interdependence between equipment efficiency and allocation policies (Yu et al., 2018). These insights reflect the capacity of DES to bridge tactical allocation with overall terminal performance outcomes.

Beyond traditional applications, predictive discrete-event simulation (PDES**)** has advanced the field by incorporating real-time data and machine learning algorithms, such as support vector machines, to predict operation times more accurately (Park et al., 2024). This predictive capability moves simulation from a static planning tool toward a dynamic decision-making mechanism, capable of adapting to uncertainty and variability in terminal operations. Such advancements align with recent research advocating for simulation-based optimization frameworks that integrate stochastic processes, nonlinear constraints, and parallel computing to improve computational efficiency (Li & Wang, 2008).

Another significant outcome revealed in the expanded review is the role of simulation optimization and DSS in enhancing operational decisions. For example, the integration of optimization tools within DES models has been shown to improve berth allocation and resource deployment strategies, thereby aligning simulation outcomes with managerial decision-making needs (Ursavas, 2022). Similarly, DSS applications demonstrate how simulation can test multiple scenarios under varying conditions, enabling sensitivity analyses that inform robust allocation policies. This approach addresses the block planning problem, where simulation-based optimization supports assigning containers to yard blocks under complex constraints (Schwientek et al., 2020).

From a strategic perspective, DES has also been widely applied to terminal expansion and long-term planning. Ambrosino and Tànfani (2009) employed DES to evaluate expansion scenarios at the Genoa terminal, demonstrating how simulation can inform investment decisions by quantifying impacts on import/export flows, equipment deployment, and handling techniques. Complementarily, sustainable expansion models specifically addressing prime mover requirements have been developed, highlighting the need to balance expansion costs with operational efficiency and environmental considerations (Loke et al., 2015). These models reinforce the value of simulation not only for immediate operational improvements but also for guiding large-scale infrastructure investments.

The results further highlight the growing attention to operational efficiency and sustainability. Dynamic discrete-time queue models have been proposed to optimize prime mover allocation under resource constraints, achieving notable improvements in system throughput (Wanigasekara & Torres, 2024). In addition, DES has been used to evaluate environmental impacts, with new terminal layout designs demonstrating that simulation can reduce emissions and improve overall sustainability performance (Abu-Aisha et al., 2021). Integrating sustainability indicators within simulation studies represents a significant step forward, ensuring that efficiency gains are aligned with environmental performance metrics.

Finally, the expanded summary indicates shifts in current industry practices, where simulation is increasingly used with algorithms to forecast expansion requirements, calculate incremental prime mover needs, and minimize opportunity costs (Loke et al., 2015). 3D visualization within DES further enhances decision-making by validating performance in automated container terminals, offering stakeholders a more intuitive understanding of complex interactions (Chase et al., 2019). These practices demonstrate that the industry is transitioning from traditional micro-simulation analyses to advanced, integrated models capable of balancing performance, cost, and sustainability objectives.

Overall, the results suggest that DES has matured into a versatile tool supporting operational optimization and strategic planning in container terminals. While early studies emphasized problem-specific solutions, contemporary approaches highlight the integration of real-time data, hybrid optimization, and sustainability considerations. This shift positions DES as an indispensable framework for addressing the challenges of prime mover allocation, enabling terminals to respond to growing trade demands while pursuing long-term resilience and environmental responsibility.

Table 1 is a concise citation impact focused on prime-mover allocation or horizontal transport and DES in container terminals. The results reveal a clear distinction between highly cited, moderately cited, and emerging contributions, reflecting both the maturity of certain research areas and the emergence of new directions.

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Table 1: Citation Impact of Key Studies on Prime Mover Allocation using DES

Author(s)	Year	Title	Source title	Citations
Jonker, T., Duinkerken, M.B., Yorke-Smith, N. de Waal, A.	2021	Coordinated optimization of equipment operations in a container terminal	Flexible Services and Manufacturing Journal	76
Ursavas, E.	2022	Priority control of berth allocation problem in container terminals	Annals of Operations Research	37
Zhou, C., Zhao, Q., Li, H.	2021	Simulation optimization iteration approach on traffic-integrated yard allocation problem in transshipment terminals	Flexible Services and Manufacturing Journal	19
Yu, H., Ge, Y. E., Fu, X., Tan, C.	2018	Capturing effects of container location dispersion on quay crane performance	Proceedings of the ICE – Maritime Engineering	10
Kastner, M., Pache, H., Jahn, C.	2019	Simulation-based optimization at container terminals: A literature review	Hamburg International Conference of Logistics (HICL) Proceedings	8
Schwientek, A. K.; Lange, A. K., Jahn, C.	2020	Effects of terminal size, yard block assignment, and dispatching methods on container terminal performance	Winter Simulation Conference (WSC) Proceedings	7
Li, H. Y., Wang, D. W.	2008	Parallel simulation-based optimization on block planning of container terminals	Journal of North-eastern University (Natural Science)	6
Abu-Aisha, T., Ouhimmou, M., Paquet, M.	2021	A simulation approach towards a sustainable and efficient container terminal layout design	Journal of International Maritime Safety, Environmental Affairs, and Shipping	4
Park, K., Kim, M., Bae, H.	2024	A predictive discrete-event simulation for predicting operation times in container terminal	IEEE Access	3

The citation impact analysis of key studies on prime mover allocation using DES highlights the maturity of certain research areas and the emergence of new directions within container terminal operations. These works demonstrate how DES has evolved from early problem-specific applications toward comprehensive frameworks integrating optimization, predictive analytics, and sustainability considerations.

Journal of Information System and Technology Management JISTM
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The most influential contributions are those of Jonker et al. (2021) with 76 citations and Ursavas (2022) with 37 citations. These studies focus on coordinated optimization of equipment operations and priority control of berth allocation, respectively, and have become central references in port logistics and operational research. Their high citation counts indicate their importance as foundational works that continue to shape ongoing research in the field.

Similarly, Zhou, Zhao, and Li (2021), with 19 citations, contributed significantly by integrating yard allocation with vehicle congestion through simulation optimization. Their study demonstrates the importance of linking traffic dynamics with allocation decisions, offering a methodological advancement that balances theoretical rigor with applied relevance. The impact of this work lies in its iterative optimization approach, which has become a reference point for simulation-based decision support in container logistics.

On the operational side, Yu et al. (2018) provided valuable insights into how container location dispersion affects QC performance, attracting 10 citations. This study illustrates the strong interdependency between prime mover allocation and QC productivity, highlighting how vehicle assignment decisions can directly influence handling efficiency. Though more narrowly focused, its findings contribute to understanding the micro-level operational drivers of efficiency.

In contrast, more recent contributions such as Park, Kim, and Bae (2024), with 3 citations to date, illustrate the emerging frontier of PDES. This study signals the transition from static simulation toward adaptive and predictive systems by incorporating real-time data and machine learning into DES frameworks. While still at an early stage regarding citation impact, its novelty and methodological innovation suggest strong potential for future influence. Likewise, Abu-Aisha, Ouhimmou, and Paquet (2021), with 4 citations, expanded the discussion to sustainability, demonstrating how simulation can evaluate terminal layouts to reduce emissions while maintaining efficiency. This represents a shift toward integrating environmental objectives alongside operational performance.

Overall, the citation analysis highlights three layers of influence: core references that are already well established, mid-tier works that are steadily gaining recognition, and emerging studies that represent the next research frontier. This pattern suggests that while traditional DES applications remain highly influential, there is a noticeable shift toward sustainability-oriented and machine learning–driven approaches, which hold significant potential to reshape the future of prime mover allocation research.

Concept Map

Insights from the Concept Map further highlighted the interconnectedness of research domains. Clusters emerged around efficiency-driven studies, sustainability-focused frameworks, and strategic planning models, suggesting that the field has matured from operational problem-solving toward a broader systemic approach. The visualization demonstrated how key constructs such as optimization, prime mover allocation, and strategic planning are interwoven, reflecting an evolution of DES applications from narrow technical solutions to more holistic frameworks for terminal management (Ursavas, 2022; Abu-Aisha et al., 2021).

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Figure 2 is generated by Scopus AI visually represents the conceptual structure of research on prime mover allocation in container terminals. At its core, the diagram places "Prime Mover Allocation in Container Terminals" as the central theme, with three major research dimensions branching out: Performance Evaluation, Optimization Methods, and Simulation Techniques.

The first dimension, performance evaluation, emphasizes how studies assess the effectiveness of prime mover allocation. Subthemes such as logistics, container rehandling, risk assessment, and performance indices indicate that evaluation extends beyond simple operational throughput to include reliability, resilience, and process efficiency. These elements highlight how prime mover allocation impacts broader terminal performance, including cargo flow, handling quality, and risk mitigation.

The second dimension, optimization methods, reflects the methodological backbone of research in this area. Subtopics such as container stacking and genetic algorithms suggest that operational rules and advanced heuristic methods are applied to improve allocation strategies. These methods are particularly valuable for solving complex resource distribution problems where traditional deterministic approaches are insufficient.

The third dimension, simulation techniques, underscores the methodological role of simulation in exploring allocation strategies. Subthemes include simulation platforms and DES, the latter being the most widely used technique for modeling dynamic and stochastic processes in terminal operations. This demonstrates how simulation provides a testbed for analyzing different allocation policies before implementation, reducing risks and costs for terminal operators.

Figure 2 reveals the multi-layered research landscape: performance evaluation ensures relevance and applicability, and optimization methods provide problem-solving approaches. Simulation techniques offer analytical and predictive frameworks. These clusters show that prime mover allocation has evolved into a multidisciplinary field, combining logistics, operations research, and simulation science to enhance container terminal efficiency and sustainability.

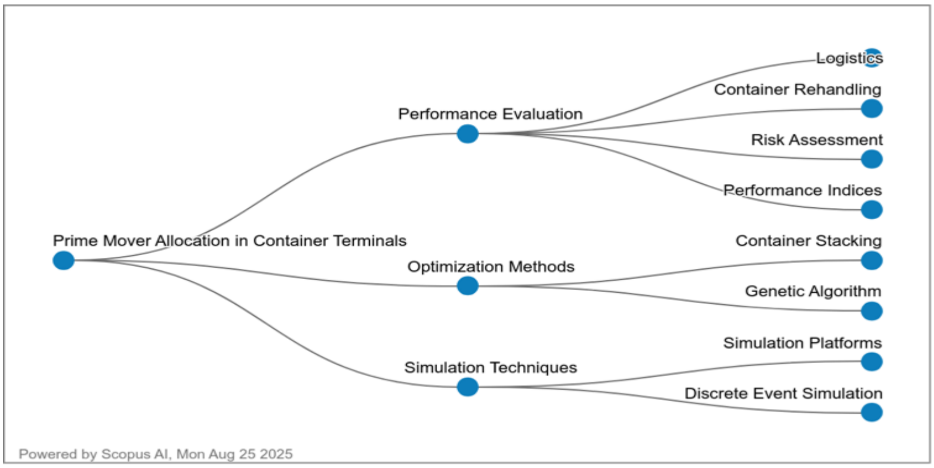

Figure 2: Concept map of Prime Mover Allocation In Container Terminals

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The Relationship Between Prime Mover Allocation and Performance Evaluation

The allocation of prime movers in container terminals is closely tied to performance evaluation because prime movers represent the core link between QCs and yard cranes (YCs). Inefficient allocation leads to congestion, delays, and underutilization of equipment, affecting vessel turnaround times and overall terminal productivity (Yu et al., 2018). Performance evaluation in this context is typically measured through indices such as gross moves per hour, container rehandling rates, and resource utilization levels. Researchers and practitioners can determine how allocation strategies directly influence operational efficiency and service quality by assessing these indicators.

Studies have demonstrated that simulation-based performance evaluation allows terminal operators to quantify the effects of different allocation strategies. For example, DES models that integrate yard allocation with vehicle congestion showed that optimized allocation could significantly reduce traffic bottlenecks and enhance throughput (Zhou et al., 2021). Similarly, by evaluating how container location dispersion impacts QC productivity, performance evaluation revealed that balanced allocation strategies minimize unnecessary rehandling, ultimately improving equipment efficiency and reducing operational costs (Yu et al., 2018). These findings highlight the importance of aligning allocation strategies with measurable performance outcomes.

Performance evaluation also extends beyond productivity to include risk assessment and resilience. Terminal operations are inherently stochastic, and poor allocation of prime movers can exacerbate delays during peak demand or equipment failures. Simulation-based evaluation frameworks incorporating risk analysis allow managers to assess robust allocation strategies under varying conditions (Wanigasekara & Torres, 2024). For instance, scenario-based evaluations demonstrate that adaptive allocation policies, such as dynamically reassigning prime movers in response to real-time yard conditions, can mitigate delays and improve system resilience. Thus, performance evaluation is a diagnostic and predictive tool for managing uncertainty in terminal operations.

Another critical dimension of performance evaluation is sustainability. With increasing regulatory and environmental pressures, prime mover allocation is no longer judged solely on operational efficiency but also on energy consumption and emissions. Abu-Aisha, Ouhimmou, and Paquet (2021) demonstrated through simulation that alternative terminal layouts and optimized vehicle deployment strategies could reduce emissions while maintaining high service levels. Similarly, sustainable expansion models for prime movers have been developed to evaluate long-term environmental and economic trade-offs (Loke et al., 2015). By integrating sustainability metrics into performance evaluation, allocation strategies can be assessed holistically, balancing efficiency, cost, and environmental impacts.

In conclusion, performance evaluation provides a vital lens for understanding the effectiveness of prime mover allocation in container terminals. It measures productivity and efficiency and considers risk management and sustainability. Simulation models, supported by performance indices and scenario analysis, enable comprehensive evaluation of allocation strategies before implementation. This integrated approach ensures that prime mover deployment supports short-term operational efficiency and long-term strategic objectives, positioning terminals to remain competitive in an increasingly demanding global trade environment.

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The Relationship Between Prime Mover Allocation and Optimization Methods

Prime mover allocation in container terminals is a complex optimization problem due to port operations' stochastic and dynamic nature. Terminal managers must determine how to allocate limited prime mover resources among multiple QCs and YCs while accounting for vessel arrival variability, container types, and yard space constraints. Poor allocation can result in bottlenecks, idle equipment, and increased vessel turnaround time. Consequently, optimization methods have been widely applied to design efficient allocation strategies that maximize resource utilization and minimize operational delays (Zhou et al., 2021).

One of the most common approaches involves simulation-based optimization, where DES is combined with optimization algorithms to evaluate multiple allocation strategies under varying conditions. For instance, Zhou et al. (2021) developed a simulation optimization framework to integrate yard allocation with prime mover traffic flows, showing that optimized allocations reduce congestion and enhance overall throughput. Similarly, Li and Wang (2008) introduced a parallel simulation-based optimization model to address block planning challenges, significantly improving computational efficiency in large-scale terminal allocation problems. These studies highlight the synergy between simulation and optimization in tackling the inherent complexity of container terminal operations.

Optimization methods also play a crucial role in aligning prime mover allocation with strategic and sustainable objectives. Loke et al. (2015) proposed a sustainable expansion model that applies optimization algorithms to determine the incremental prime mover requirements for future growth, while minimizing costs and environmental impacts. Similarly, DSS embedded with optimization techniques have been developed to prioritize berth allocation and yard block assignment, enabling managers to optimize multiple resources simultaneously (Ursavas, 2022). These applications illustrate how optimization methods extend beyond short-term operational efficiency to long-term strategic planning and sustainable resource deployment.

In conclusion, the relationship between prime mover allocation and optimization methods underscores the importance of advanced analytical approaches in enhancing terminal efficiency. Simulation optimization frameworks provide realistic assessments of allocation strategies under uncertainty, while heuristic algorithms such as genetic algorithms enable flexible and adaptive solutions. Moreover, optimization models incorporating sustainability objectives ensure that allocation decisions balance efficiency, cost, and environmental performance. These methods position optimization as an indispensable tool for improving prime mover allocation in container terminals, supporting operational excellence and long-term competitiveness.

The Relationship Between Prime Mover Allocation and Simulation Techniques

Simulation techniques are central in analyzing and optimizing prime mover allocation in container terminals. Because container terminals operate in a highly dynamic environment where multiple subsystems QCs, YCs, and transport vehicles interact simultaneously, analytical models alone are often insufficient to capture real-world complexity. Simulation enables researchers and practitioners to replicate operational processes, evaluate allocation strategies, and forecast outcomes under different scenarios. Among these, DES has become the dominant approach for modeling prime mover flows due to its ability to handle stochastic events and sequential dependencies in terminal operations (Zhou et al., 2021).

Journal of Information System and Technology Management JISTM
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The application of DES provides insights into how prime movers influence operational efficiency and system-wide coordination. For example, Yu et al. (2018) showed through simulation that inefficient allocation of prime movers can negatively affect QC productivity by increasing waiting times and rehandling. Similarly, simulation of integrated yard and traffic allocation revealed that optimized deployment of prime movers reduces congestion and enhances overall container throughput (Zhou et al., 2021). These studies highlight that DES is not only a tool for operational analysis but also a decision-support mechanism that links allocation strategies to measurable performance outcomes.

Recent advancements have expanded simulation techniques beyond traditional DES to include predictive and hybrid simulation models. PDES, which integrates real-time data and machine learning, has been used to forecast operation times and dynamically adjust prime mover allocation (Park et al., 2024). Parallel simulation-based optimization frameworks have also been introduced to address computational challenges in large-scale yard and block planning, thereby enabling faster evaluation of allocation scenarios (Li & Wang, 2008). These innovations demonstrate the evolution of simulation from static representations to adaptive and intelligent systems capable of supporting real-time decision-making.

Simulation techniques are also critical in validating and testing advanced optimization algorithms for prime mover allocation. For instance, heuristic methods such as genetic algorithms are often embedded within simulation environments to evaluate their effectiveness under stochastic conditions (Almeder et al., 2009). Furthermore, 3D simulation and visualization platforms have been applied to assess automated terminal designs and vehicle coordination, providing managers with more intuitive and practical evaluations of allocation strategies (Chase et al., 2019). Such approaches bridge the gap between theoretical optimization and practical implementation, ensuring that allocation policies are operationally feasible and performance-driven.

Finally, simulation has been increasingly applied to evaluate the prime mover allocation's sustainability and resilience dimensions. Abu-Aisha, Ouhimmou, and Paquet (2021) demonstrated how simulation of alternative terminal layouts could reduce emissions without compromising service levels. Similarly, Loke et al. (2015) developed a sustainable expansion model using simulation to forecast long-term prime mover requirements while minimizing environmental and financial costs. These examples highlight the versatility of simulation techniques in addressing operational efficiency and broader strategic goals, such as resilience under demand fluctuations and compliance with environmental standards.

In conclusion, simulation techniques, particularly DES and its advanced variants, are indispensable in understanding and optimizing prime mover allocation in container terminals. They enable realistic modeling of complex operations, integration of predictive analytics, validation of optimization algorithms, and evaluation of sustainability objectives. By combining operational detail with strategic foresight, simulation techniques provide a comprehensive framework for aligning prime mover allocation with the dual imperatives of efficiency and long-term competitiveness in global port operations.

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Topic Expert

A review of the citation network reveals several influential scholars who have shaped the intellectual trajectory of research in simulation-based port logistics. For instance, Zhou et al. (2021) advanced simulation-optimization techniques for yard allocation, while Yu et al. (2018) offered important perspectives on QC productivity under different container distributions. Earlier contributions, such as Ambrosino and Tànfani's (2009) pioneering application of DES to terminal expansion planning, laid the groundwork for long-term strategic modelling in this domain. More recently, Schwientek et al. (2020) examined dispatching methods and the implications of terminal size, further expanding the scope of inquiry. Together, these studies and the institutions behind them form the central knowledge clusters driving both theoretical and applied innovations in port logistics research.

Identifying leading scholars is valuable because it highlights the individuals who are guiding methodological and conceptual progress in prime mover allocation. Publication patterns, citation records, and research outputs show that a handful of researchers have played a particularly strong role in developing simulation methods, predictive tools, and optimization strategies. Among these, Hye-Rim Bae, Kikun Park, and Minseop Kim stand out, with their collective work illustrating the increasing importance of predictive DES in tackling the operational complexities of resource allocation in container terminals.

Hye-Rim Bae is widely regarded as a central figure in the field, with more than 1,200 citations and an h-index of 19, a clear indicator of the breadth and influence of their work. Much of Bae's research has focused on predictive DES models tailored to container terminal operations (Park, Kim, & Bae, 2024). This body of work has direct implications for prime mover allocation, particularly by anticipating congestion points, estimating operation times, and identifying resource bottlenecks. By integrating real-time data into simulation environments, Bae has shown how predictive analytics can be used to strengthen decision-making, minimize delays, and improve overall efficiency. The consistent recognition of this research in the literature underscores its value for both academic inquiry and operational practice.

Kikun Park, while still building a scholarly profile, has also made noteworthy contributions. With 68 citations and an h-index of 3, Park's recent co-authored work on predictive DES has been especially relevant for modelling terminal operations in uncertain conditions (Park et al., 2024). These studies are significant for prime mover allocation because they highlight adaptive resource assignment strategies that can respond to varying workloads. Although Park's citation record is more modest, the methodological focus of their work enhances the field by bridging theoretical developments with practical applications. As predictive modelling continues to gain prominence, Park's role in shaping this area of study is likely to expand.

Minseop Kim represents an early-career scholar whose contributions, though limited in citation count, show strong potential for future influence. Kim's work demonstrates a commitment to refining predictive DES for container terminal contexts, with an emphasis on the ways these tools can support resource allocation decisions. Despite being relatively new to the field, Kim's perspective introduces fresh ideas, particularly regarding the balance between prime mover deployment and broader terminal operations. This forward-looking orientation suggests that as Kim continues to publish, their contributions will increasingly shape ongoing debates and innovations in simulation-based logistics research.

Collectively, the work of Bae, Park, and Kim illustrates the way topic experts are driving the methodological evolution of simulation in prime mover allocation research. Bae's established expertise ensures a strong foundation of credibility, Park's developing contributions emphasize the practical potential of predictive approaches, and Kim's emerging scholarship brings fresh innovation to the discourse. The growing integration of predictive simulation into allocation strategies reflects a wider trend in the literature toward adaptive, data-driven, and sustainable decision-making. This convergence between individual contributions and thematic developments underscores the pivotal role that expert researchers play in advancing both the theory and practice of port logistics.

Emerging Themes

The analysis also uncovered several emerging themes that signify the direction of future research. One prominent theme is the integration of machine learning with DES for predictive and adaptive terminal operations (Park et al., 2024). Another growing area is the incorporation of sustainability metrics, including carbon footprint reduction and green resource allocation models, reflecting the rising importance of environmentally conscious logistics (Abu-Aisha et al., 2021). A third emerging theme is the development of dynamic decision support systems, which enable real-time resource allocation under uncertainty and fluctuating demand (Ursavas, 2022). Together, these themes suggest that the next generation of research will move beyond static efficiency optimization to embrace adaptive, resilient, and sustainable strategies for prime mover allocation.

The analysis of emerging themes in prime mover allocation and container terminal operations reveals three distinct strands of development: consistent themes that reflect long-standing priorities in port research, rising themes that represent growing areas of academic and industrial interest, and novel themes that highlight cutting-edge methodologies with the potential to reshape future research. Collectively, these themes demonstrate how the field is evolving from traditional optimization to advanced, adaptive, and data-driven approaches, while maintaining a strong focus on operational efficiency and sustainability.

In summary, the emerging themes reflect a layered progression of research priorities in container terminal operations. Integrated scheduling and DES remain consistent pillars that ensure operational efficiency and predictability. Rising themes such as sustainability and DSS highlight the evolving emphasis on adaptive, environmentally conscious resource allocation. Finally, novel approaches such as Boolean and algebraic methods represent innovative directions that could reshape how control and optimization are conceptualized in container terminal systems. Together, these themes illustrate the dynamic interplay between established methodologies and pioneering research, positioning prime mover allocation as both a practical challenge and a fertile ground for theoretical advancement.

Consistent Theme: Integrated Scheduling and Optimization, DES in Container Terminal Operations

A consistent theme across the literature is the integration of scheduling and optimization techniques to improve container terminal performance. This involves aligning berth allocation, QC scheduling, and equipment management, particularly prime mover deployment, to ensure seamless coordination of resources. Studies have demonstrated that integrated scheduling frameworks can reduce operational costs, minimize vessel turnaround time, and improve throughput by optimizing multiple interdependent processes (Ursavas, 2022; Zhou et al., 2021). For instance, combining berth allocation with dynamic QC assignment has been shown to balance workloads across resources, while prime mover allocation strategies reduce idle times and congestion. The resilience of terminal operations is also strengthened by embedding advanced optimization algorithms, which enable rapid adjustments under uncertainty such as vessel delays or fluctuating container volumes (Schwientek et al., 2020). These findings suggest that integrated scheduling and optimization remain indispensable for ensuring both efficiency and sustainability in terminal management.

Another consistent theme is the enduring use of DES in modeling container terminal operations. DES remains a cornerstone methodology for evaluating prime mover allocation strategies, predicting operation times, and analyzing system bottlenecks under stochastic conditions. Research has consistently demonstrated that DES provides accurate forecasts of resource requirements, enabling terminal managers to evaluate alternative strategies before implementation (Yu et al., 2018; Park, Kim, & Bae, 2024). For example, simulation models have been applied to assess the impact of yard allocation policies on prime mover traffic, revealing that optimized allocation reduces waiting times and enhances QC productivity (Zhou et al., 2021). Moreover, simulation-based approaches offer the flexibility to conduct scenario analysis, identifying key factors such as container dispersion and YC availability that influence overall efficiency. By serving as both a diagnostic and predictive tool, DES continues to reinforce evidence-based decision-making in container terminal operations.

Rising Theme: Sustainability-Oriented Optimization and Decision Support

A rising theme in container terminal research is the integration of sustainability considerations and DSS into optimization models. With growing environmental pressures and regulatory demands, prime mover allocation is increasingly assessed not only for its contribution to efficiency but also for its role in reducing fuel consumption and emissions. Studies such as Abu-Aisha, Ouhimmou, and Paquet (2021) demonstrate that optimized terminal layouts and vehicle deployment strategies can substantially lower emissions while maintaining high productivity. In parallel, Loke et al. (2015) introduced a sustainable expansion model for prime movers, illustrating how optimization frameworks can reconcile operational growth with long-term environmental objectives.

Complementing these sustainability-driven approaches, DSS embedded with simulation and optimization techniques enable real-time adaptive resource allocation, allowing terminal managers to respond effectively to fluctuating demand and operational uncertainties. Ursavas (2022) emphasized the value of such systems in aligning decision-making with both performance and sustainability goals, ensuring that environmental considerations are integrated into everyday operations. Together, these developments indicate that sustainability-oriented optimization has moved from a peripheral concern to a central dimension of both academic research and industry practice, shaping the future of prime mover allocation strategies in container terminals.

Novel Theme: Boolean and Algebraic Methods in Discrete-Event Systems

The novel theme identified in the literature is the application of Boolean and algebraic methods in discrete-event systems, which introduces new possibilities for control and fault diagnosis in container terminal operations. Approaches such as Boolean semantic modelling, Petri nets, and tropical-algebraic methods provide a mathematical framework for analyzing the logical structure of complex systems, enabling more robust fault detection, system reconfiguration, and operational control (Ramadge & Wonham, 1989; Giua, 2019). While these methods are still in the exploratory stage within the context of port operations, they offer promising avenues for improving the reliability of prime mover allocation under uncertainty. For instance, Petri net-based models have been successfully applied in manufacturing and logistics to diagnose disruptions and reallocate resources dynamically, suggesting that similar applications could enhance resilience in container terminals. This theme signals the entry of advanced mathematical tools into the domain, offering new frontiers for research that complement existing simulation and optimization approaches.

In summary, the emerging themes reflect a layered progression of research priorities in container terminal operations. Integrated scheduling and DES remain consistent pillars that ensure operational efficiency and predictability. Rising themes such as sustainability and DSS highlight the evolving emphasis on adaptive, environmentally conscious resource allocation. Finally, novel approaches such as Boolean and algebraic methods represent innovative directions that could reshape how control and optimization are conceptualized in container terminal systems. Together, these themes illustrate the dynamic interplay between established methodologies and pioneering research, positioning prime mover allocation as both a practical challenge and a fertile ground for theoretical advancement.

Conclusion

This review examined the role of DES and related analytical approaches in enhancing prime mover allocation within container terminals. By synthesizing insights from the Scopus AI outputs including summaries, expanded summaries, concept maps, topic experts, and emerging themes, this study provided a holistic understanding of how simulation, optimization, and scheduling techniques have been applied to address operational challenges in modern port logistics.

The findings demonstrate that prime mover allocation is a pivotal determinant of container terminal efficiency, directly influencing QC productivity, yard operations, and vessel turnaround time (Yu et al., 2018; Zhou et al., 2021). DES emerged as a consistent and powerful methodology for evaluating allocation strategies under stochastic and dynamic conditions, offering both diagnostic and predictive capabilities (Park, Kim, & Bae, 2024). Optimization methods, including simulation-based optimization and heuristic algorithms, were shown to significantly reduce congestion and operational costs while improving throughput (Ursavas, 2022). Additionally, sustainability-focused models highlighted the importance of balancing efficiency with environmental performance, particularly in reducing fuel consumption and emissions from prime movers (Abu-Aisha, Ouhimmou, & Paquet, 2021; Loke et al., 2015). Emerging themes such as predictive DES, machine learning integration, and Boolean-algebraic methods further underscore the field’s shift toward adaptive and intelligent decision-support systems.

From a theoretical perspective, this study contributes to the literature by framing prime mover allocation as both an operational optimization problem and a strategic systems problem. The integration of DES with optimization and decision-support frameworks advances theories of resource allocation in stochastic environments by linking simulation outputs with real-time decision-making. Moreover, the identification of consistent, rising, and novel themes demonstrates the evolutionary trajectory of container terminal research from deterministic models to hybrid, data-driven, and sustainability-oriented frameworks. This conceptual progression enriches the theoretical discourse on logistics optimization and complex system modeling.

Practically, the review provides valuable insights for terminal managers, port authorities, and policymakers. Integrated scheduling and optimization frameworks can be directly applied to reduce vessel turnaround times and operational costs, ensuring higher competitiveness in global trade. Predictive simulation and decision-support systems offer tools for real-time resource allocation, enabling managers to respond to demand fluctuations and disruptions more effectively. Importantly, the incorporation of sustainability metrics into prime mover allocation highlights actionable pathways for ports to align operational efficiency with environmental regulations and green logistics initiatives. Thus, the findings bridge the gap between academic modeling and managerial practice, providing concrete strategies for enhancing both efficiency and sustainability in terminal operations.

Despite its comprehensive scope, this study has several limitations. First, the reliance on Scopus AI analytics constrains the dataset to indexed publications, potentially overlooking relevant industry reports, non-indexed conference papers, and grey literature. Second, the review synthesizes findings across diverse contexts, but container terminal operations are highly location-specific, influenced by local infrastructure, policy, and demand patterns. Third, while the review highlights emerging themes such as machine learning and Boolean-algebraic methods, empirical applications in real-world terminals remain limited, making it difficult to generalize their effectiveness at this stage.

Future research should focus on several directions. First, there is a need for empirical validation of predictive DES and hybrid optimization models in real-world container terminals, particularly under disruptive conditions such as pandemics or extreme weather events. Second, research should expand the scope of performance evaluation to include comprehensive sustainability indicators, integrating emissions, energy efficiency, and resilience alongside traditional efficiency metrics. Third, interdisciplinary approaches that combine simulation with artificial intelligence, digital twins, and Internet of Things (IoT) technologies should be further explored to enhance real-time decision-making. Finally, future studies should examine policy and governance frameworks for implementing advanced optimization systems, addressing issues such as cost, scalability, and cross-terminal collaboration.

In summary, this review underscores that simulation-based approaches, when combined with optimization and predictive modeling, provide a robust framework for improving prime mover allocation in container terminals. By advancing both theoretical understanding and practical application, the study contributes to building more efficient, resilient, and sustainable terminal operations, while paving the way for future innovations in smart port logistics.

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