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Optimizing Container Terminal Operations: A Comparative Analysis of Hierarchical and Integrated Solution Approaches

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ABSTRACT: Container terminals serve as crucial hubs in the global supply chain, facilitating the efficient transfer of goods between different modes of transportation. This study explores optimization strategies for container terminal operations, focusing on the comparison between hierarchical and integrated solution approaches. A comprehensive literature review provides insights into the challenges and advancements in container terminal management. The comparative analysis highlights the advantages of integrated optimization models, particularly through the lens of the Tactical Berth Allocation Problem (TBAP). By incorporating real-world data and advanced computational methods, the study offers nuanced insights into efficiency and time estimation aspects.

1 INTRODUCTION

A container terminal operates as a bustling hub, where goods transition between different modes of transportation. It comprises two primary areas: the quayside and the landside. The quayside hosts berthing positions and quay cranes for efficiently loading and unloading containers from ships. Once offloaded, containers embark on the next leg of their journey to the yard, facilitated by automatic guided vehicles, straddle carriers, or internal trucks. However, congestion in the yard can impede this flow, causing delays and undermining operational efficiency (see Figure).

Decision-making in container terminal operations spans four key areas. Firstly, berth allocation and scheduling involve the strategic assignment of ships to berths or quay locations, carefully balancing operational demands within a designated timeframe. Secondly, quay crane allocation and scheduling focus on optimizing the assignment of quay cranes to vessels, ensuring a smooth and timely loading, and unloading process. Thirdly, transfer operations entail the movement of containers between the quayside, yard, and gate, necessitating effective vehicle routing and dispatching strategies. Lastly, storage and stacking strategies are devised at the block level, with containers allocated specific positions based on their attributes and operational requirements. These operational components collectively drive the efficiency and effectiveness of container terminal operations.

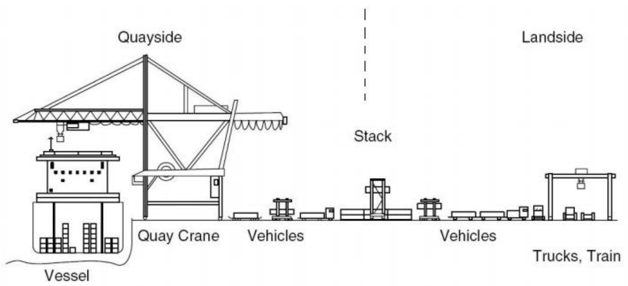

Figure 1. Schematic representation of a container terminal (Steenken et al., 2004).

2 LITERATURE REVIEW:

2.1 *Container Terminal Operations*

Container terminal operations are vital nodes in global supply chains, facilitating the seamless transfer of goods across various transportation modes. Researchers have extensively explored the complexities inherent in these operations. For instance, Weerasinghe et al. (2023) offer a systematic review of optimization methodologies in container terminals, shedding light on strategies to enhance efficiency in berth allocation, yard planning, and equipment scheduling. Meanwhile, Raeesi et al. (2023) delve into the synergy between operational research and big data analytics, aiming to promote environmentally sustainable practices within container terminal operations. Additionally, Gao and Ge (2022) focus on integrated scheduling strategies for yard cranes and trucks, emphasizing holistic approaches to enhance terminal efficiency.

2.2 *Integrated Optimization Strategies:*

Integrated optimization has emerged as a promising avenue to bolster overall efficiency in container terminal operations. Che et al. (2023) explore planning strategies in highly electrified terminals, considering time-of-use tariffs to promote sustainability. Comparative studies by Al Samrout et al. (2024) highlight the superiority of integrated optimization over traditional methods, particularly in berth scheduling with ship-to-ship transshipment operations. Similarly, Cao et al. (2023) demonstrate the advantages of integrated optimization in automated container terminals, focusing on AGV dispatching and routing problems. These studies underscore the importance of integrated approaches in addressing operational complexities.

2.3 *Traffic Congestion Analysis:*

Traffic congestion poses significant challenges to container terminal operations, impacting efficiency and sustainability. Innovative approaches, such as multi-agent reinforcement learning for AGV path planning (Hu et al., 2021), and deep learning for port congestion prediction (Peng et al., 2022), offer insights into mitigating congestion dynamics. Strategies like dynamic scheduling, explored by Xiang et al. (2023), aim to adapt to changing operational environments, enhancing overall terminal performance. Wang et al. (2024) delve into scheduling strategies for equipment transfer modes, further contributing to congestion alleviation efforts.

2.4 *Tactical Planning:*

Tactical planning plays a crucial role in optimizing resource allocation and capacity planning within container terminals. Studies by Cartenì and de Luca (2012) and Yang et al. (2013) delve into the intricacies of tactical planning, addressing issues such as equipment maintenance scheduling and truck arrival management. Gumuskaya et al. (2020) explore dynamic barge planning strategies, considering stochastic container arrivals to enhance operational efficiency. These studies underscore the significance of tactical planning in ensuring long-term operational sustainability.

2.5 *State-of-the-Art Optimization Approaches:*

Recent advancements in optimization techniques have revolutionized container terminal operations, providing decision-makers with powerful tools to address complex challenges. Ambrosino and Xie (2022) investigate optimization approaches for defining storage strategies, aiming to improve space utilization and operational efficiency. Hsu et al. (2022) explore heuristic-based simulation optimization for integrated scheduling, offering insights into enhancing scheduling efficiency. Drungilas et al. (2023) utilize deep reinforcement learning to optimize AGV operations, emphasizing improvements in time and energy consumption. These studies highlight the transformative potential of advanced optimization techniques in enhancing container terminal operations.

2.6 *Current Research Trends:*

The landscape of container terminal operations continues to evolve, driven by technological innovations and emerging trends. Current research trends, including the integration of artificial intelligence, adoption of sustainable practices, and exploration of blockchain technology, offer promising avenues for future advancements. Wang et al. (2024) and Al Samrout et al. (2024) identify key trends shaping the future of container terminal operations, paving the way for innovative solutions and sustainable practices.

In summary, the literature review underscores the multidimensional nature of container terminal operations and emphasizes the importance of integrated optimization strategies in addressing operational challenges. Our study contributes to this body of knowledge by focusing on tactical planning, employing the Tactical Berth Allocation Problem (TBAP) as a case study. By incorporating congestion management and employing advanced computational methods, our research aims to provide practical insights for optimizing container terminal operations in real-world scenarios.

3 HIERARCHICAL VS INTEGRATED SOLUTION APPROACHES

When addressing complex problems like the Berth Allocation Problem (BAP) and the Quay Crane Assignment Problem (QCAP) in container terminal operations, planners often resort to either hierarchical or integrated solution approaches. Each approach offers distinct advantages and is chosen based on the problem's characteristics and the desired outcomes.

3.1 *Hierarchical Approach: BAP + QCAP*

The hierarchical approach involves solving the BAP and QCAP sequentially, breaking down the problem into manageable sub-problems. Initially, vessels are assigned to berths based on estimated handling times and time windows in the BAP step. This step aims to optimize berth template creation, considering vessel workload and scheduling robustness. Subsequently, in the QCAP step, quay cranes are allocated to vessels based on the berth allocation plan, considering workload and crane capacity constraints. This sequential optimization allows for systematic planning and efficient coordination of terminal operations.

- Berth Allocation Problem (BAP): In this step, vessels are assigned to berths to minimize yard management costs while optimizing berth template creation for efficient vessel scheduling.
- Quay Crane Assignment Problem (QCAP): Quay cranes are then assigned to vessels, ensuring that the total crane capacity is not exceeded. The objective is to maximize the monetary value associated with the assigned quay crane profiles.

In our study, we utilized models developed by Giallombardo et al. (2010) for both BAP and QCAP, aligning their objective functions with the overall objectives of the integrated TBAP model for meaningful comparison.

3.2 *Integrated Approach: TBAP*

In contrast, the integrated approach tackles both the BAP and QCAP simultaneously, aiming for greater efficiency and resource utilization. The Tactical Berth Allocation Problem (TBAP) integrates berth allocation and quay crane assignment optimization, considering the interdependencies between these decisions. This approach, introduced by Giallombardo et al. (2010), maximizes the monetary value of assigned quay cranes while minimizing management costs associated with berth allocation, thereby effectively managing congestion.

The TBAP model treats vessel handling time as a decision variable influenced by the number of assigned quay cranes, allowing for dynamic resource allocation. By integrating optimization processes traditionally solved separately, the TBAP model provides a comprehensive solution that optimizes terminal operations from a holistic perspective.

In summary, while the hierarchical approach breaks down problems into manageable steps, the integrated approach offers a more comprehensive solution by considering interdependencies and optimizing multiple aspects simultaneously. Our study explores both approaches, emphasizing the advantages and implications of each in container terminal operations optimization.

4 COMPARATIVE ANALYSIS

In our comparative analysis, we utilized both hierarchical and integrated solution approaches to address the Berth Allocation Problem (BAP) and the Quay Crane Assignment Problem (QCAP) in container terminal operations. We conducted experiments using a branch-and-price algorithm for the integrated TBAP and adapted it for the hierarchical approach in solving the BAP model. For the QCAP model, a general-purpose Mixed Integer Programming (MIP) solver was employed. Our analysis focused on comparing the performance of these approaches under different scenarios and examining their computational efficiency and solution quality.

4.1 *Handling Time Estimation*

In the hierarchical approach, handling time estimation is crucial and typically relies on input from terminal planners. Two scenarios were considered for estimating handling time: Scenario A, which uses the longest feasible quay crane assignment profile for every vessel, and Scenario B, which prioritizes mother vessels by using the shortest feasible profile for them and the longest for feeders. Both scenarios have their merits, with Scenario A providing a conservative estimate and Scenario B offering a more realistic reflection of vessel priority.

4.2 *Experimentation*

Tables 1 and 2 present a comparison of the objective function values between the integrated solution and the hierarchical approach under scenarios A and B, respectively. The integrated approach consistently outperforms the hierarchical approach, with notable improvements in objective function values across instances.

Table 1. Objective function: integrated solution vs hierarchical approach under scenario A

Instance	hierarchical approach (A)	Integrated Solution	Improvement in %
1	812167	815735	44%
2	812117	816011	48%
3	812151	816045	48%
4	755702	758276	34%
5	755418	760646	69%
6	755454	760682	69%
7	538661	540902	41%
8	538696	543049	80%
9	538731	543084	80%
10	584683	589831	87%

Table 2. Objective function; integrated solution vs hierarchical approach under Scenario B

Instance	hierarchical approach (B)	Integrated Solution	Improvement in %
1	814478	815735	15%
2	814754	816011	15%
3	814788	816045	15%
4	758276	758276	0%
5	757659	760646	39%
6	757695	760682	39%
7	540017	540902	16%
8	540052	543049	55%
9	540087	543084	55%
10	586705	589831	53%

Tables 3 and 4 provide a comparison of the time estimations for the hierarchical and integrated approaches under scenarios A and B, respectively. The integrated approach generally requires more computational time but achieves better results, indicating its effectiveness in handling complex instances.

Table 3. Time estimation; integrated solution vs hierarchical approach under Scenario A.

Hierarchical approach (A)	Integrated Solution	Time
15	114	87%
16	995	98%
16	557	97%
3	12	75%
6	29	79%
4	25	84%
85	4054	98%
21	761	97%
21	470	96%
30	4697	99%

Table 4. Time estimation; integrated solution vs hierarchical approach under Scenario B.

Hierarchical approach (B)	Integrated Solution	Time
26	114	77%
16	995	98%
16	557	97%
2	12	83%
6	29	79%
6	25	76%
308	4054	92%
171	761	78%
173	470	63%
24	4697	99%

4.3 *Interpretation*

Under both scenarios A and B, the integrated approach demonstrates superior performance in terms of objective function values compared to the hierarchical approach. Although the integrated approach requires more computational effort, it consistently finds optimal solutions within a reasonable time frame, particularly for congested instances closely resembling real-world scenarios.

In scenarios with more congestion, the limitations of the hierarchical approach become apparent, as it may struggle to provide feasible solutions due to constraints on quay crane assignments. In contrast, the integrated approach proves robust and efficient in utilizing terminal resources effectively.

While the improvement in objective function values may seem modest for cases where the hierarchical approach is feasible, every incremental gain is significant in optimizing terminal operations. The integrated TBAP approach emerges as the preferred solution, especially for congested instances, highlighting the importance of considering interdependencies in decision-making processes.

4.4 *Additional Results*

Table 5 presents the results of the week, showcasing the objective function values, berth allocations, and computational times for both the hierarchical and integrated approaches. These results further reinforce the superiority of the integrated approach in optimizing terminal operations.

Overall, our comparative analysis underscores the effectiveness of the integrated TBAP approach in achieving optimal solutions for the Berth Allocation Problem and the Quay Crane Assignment Problem in container terminal operations.

5 STUDY CONSTRAINTS AND RECOMMENDATIONS FOR FUTURE RESEARCH

While this study provides valuable insights into the optimization of container terminal operations, several limitations warrant consideration. Firstly, the contextual specificity of the dataset and models utilized may restrict the generalizability of findings to different terminal settings. Additionally, the simplified modeling assumptions and reliance on available data may overlook certain complexities inherent in real-world operations. Future research could explore the incorporation of more dynamic and realistic factors into the models. Moreover, the computational scalability of the methods employed poses challenges for larger and more complex instances, indicating a need for further advancements in optimization techniques. Addressing these limitations could enhance the robustness and applicability of optimization strategies in container terminal management.

6 CONCLUSION

In conclusion, this study has delved into the intricate domain of container terminal operations, offering a comprehensive analysis of key decision problems and optimization strategies. The literature review provided valuable insights into the pivotal role of container terminals in global supply chain management and underscored recent advancements in operational research and optimization methodologies.

Table 5. Results of the week

	BPA&QCAP (scenario A)			BPA&QCAP (scenario B)			Integrated Solution				
Instance	objective function	berths	time	objective function	berths	time	objective function	berths	time	scenario A	scenario B
1	_	_	_	_	_	_	809620	3	55	+∞	+∞
2	808553	3	11	_	_	_	811896	3	146	45%	+∞
3	808587	3	12	_	_	_	814522	3	89	78%	+∞
4	_	_	_	_	_	_	754653	3	41	+∞	+∞
5	752149	3	7	754896	3	8	756567	3	51	63%	25%
6	752220	3	5	754896	3	8	757807	3	49	80%	42%
7	539750	3	5	_	_	_	544755	2	13	101%	+∞
8	539587	3	4	540727	3	8	544755	2	103	104%	81%
9	539622	3	4	540762	3	8	545213	2	1721	112%	90%
10	586193	3	6	588401	3	11	590972	2	65	88%	48%

Through a comparative analysis of hierarchical and integrated solution approaches, particularly focusing on the Tactical Berth Allocation Problem (TBAP), intriguing findings emerged. While the hierarchical approach proved computationally efficient in less congested scenarios, it encountered difficulties in providing feasible solutions under heightened congestion. Conversely, the integrated TBAP approach consistently exhibited superior performance, delivering optimal solutions even in complex, real-world scenarios.

The integration of yard management costs into the TBAP model addressed a crucial aspect of container terminal operations, emphasizing practical implications and supporting the industry's imperative for efficient congestion management. Additionally, the consideration of multiple scenarios for handling time estimation added depth to the analysis, offering a nuanced understanding of the model's robustness and practical applicability.

The study's distinctive contributions lie in its focused exploration of tactical planning, utilizing the TBAP as a case study. By leveraging real-world data and advanced computational methods, the research presented a nuanced comparison that transcended traditional objective functions, shedding light on both efficiency and time estimation aspects.

As container terminal operations evolve in response to technological innovations and emerging trends, the insights from this study contribute to the ongoing discourse in the field. Emphasizing integrated optimization, congestion analysis, and tactical planning, the research aligns with current industry trends, highlighting the need for holistic approaches to tackle the multifaceted challenges of container terminal management.

In the ever-evolving landscape of container terminal operations, continuous exploration and adaptation are imperative. By remaining attuned to the dynamic nature of the industry, researchers and practitioners can contribute to the development of robust strategies that ensure the seamless flow of goods in the global supply chain.

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