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Cost Optimisation to determine ship maintenance schedules for improved operational availability

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Abstract

Complex port maintenance operations face significant challenges due to the dynamic nature of port resource availability, variable task urgency, and downtimes having different priorities. This study proposes a dynamic scheduling approach for ship maintenance that integrates agent-based modelling with multi-objective optimisation. By optimising port resource allocation and reducing ship idle costs, the approach significantly enhances operational efficiency in maritime logistics. Utilising a hybrid simulation-optimisation framework, the proposed method adapts downtime priorities and resource allocations rules arising due to classes of ship and their compatibility with the port resources, and their downtimes. Agent-based modelling simulates interactions between ships, port assets, and maintenance activities while Discrete Event Simulation captures the stages of maintenance process. The model re-evaluates the ship maintenance schedules and facility resource downtime schedules to minimise idle time and maximise efficiency. Comparative analyses reveal improvements over static methods, including an average 45% reduction in idle costs of ship due to unavailable resources, with marginal changes in maintenance costs. This approach not only enhances port operational efficiency but also reduces costs associated with ship waiting times, demonstrating its potential application to other complex industrial scheduling problems requiring adaptive solutions.

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Keywords: Maintenance scheduling; Hybrid optimisation; Resource allocation; Idle time reduction; Cost optimisation

1. Introduction

Maritime transport moves over 80% of global goods, positioning ports as essential hubs for sustaining trade [1]. With container throughput expected to exceed 1 billion Twenty-Foot Equivalent Units (TEUs) by 2025, port infrastructure faces unprecedented demand [2]. Simultaneously, ports are challenged to align with the International Maritime Organisation's (IMO) target of reducing greenhouse gas emissions from shipping by at least 50% by 2050 [3]. CO2 emissions from ships in ports account for approximately 6% of total maritime CO2 emissions [4]. These pressures underscore the urgent need for efficient and sustainable port operations, a challenging balance to achieve.

A primary area of complexity in port operations is managing fleet maintenance within the constraints of limited resources such as docks (sheltered areas for vessel mooring) and berths (designated spots for securing vessels). The dock is usually a dry-dock where the repair, maintenance is carried out for the ship [5]. These assets, shared across multiple port activities including maintenance, disposal, and cargo handling, often lead to operational bottlenecks and scheduling conflicts [2]. Moreover, limited resources, parallel interactions, dependencies, ship variability, and competing priorities further complicate scheduling and resource allocation, often delaying maintenance tasks, increasing operational costs, and reducing port efficiency [3]. For instance, limited resources may delay timely task completion, while dependencies between tasks can create conflicts that affect overall facility performance. Varying asset capabilities and competing priorities over time also complicate maintenance planning, resulting in costly idle times and reduced profitability [4]. The aforementioned complexities

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hinder effective resource allocation, leaving ships idle as they await maintenance availability, which in turn incurs business losses with each additional day of non-operation. Traditional analytical and mathematical models often struggle to capture the dynamic and interdependent nature of port processes, as they become time-intensive and error-prone with rising complexity [6]. To address these limitations, this study proposes a simulation-based optimisation model designed to capture the variability in port maintenance over time, including differences in ship classes (e.g. varying ship sizes and maintenance requirements) and the upkeep of port resources, such as dock downtime. The model identifies a cost-effective maintenance strategy providing a practical solution to modern port management challenges. This study addresses two research questions:

I. What is the minimum maintenance cost required to optimise schedules and reduce idle time while maintaining ship availability at a specified level of demand?
II. How can port resource allocation be improved to achieve optimal maintenance schedules?

Based on these questions, the paper develops a methodology for ship maintenance scheduling that enhances operational availability while optimising maintenance costs. This research contributes to maritime asset management by introducing an adaptive, simulation-based approach to maintenance scheduling, with potential benefits for operational efficiency, resource utilisation, and cost-effectiveness in a dynamic maritime port environment. The remainder of this paper is organised as follows: Section 2 reviews existing research on optimisation approaches for ship maintenance schedules. Section 3 describes the methodology used to develop the proposed model. Section 4 presents a case study implementing this methodology, and its results. Finally, Section 5 discusses conclusions and potential future work.

2. Related Works

Recent research in maritime resource allocation and scheduling have employed various approaches, from dynamic scheduling to heuristic optimisation and hybrid models, all aimed at improving port efficiency, reducing idle times, and optimising ship operations. Dynamic scheduling and cost optimisation techniques have demonstrated promising results for enhancing port efficiency, particularly in managing ship loading and maintenance. Tian et al. [7] developed a method to optimise ship loading operations while considering port equipment downtimes, reducing idle periods and maintenance costs of ship. Similarly, Jia et al. [8] developed a two-step decision making algorithm to handle unpredictable ship arrivals, assigning ships to docks and adjusting service times based on arrival schedules. Bebic et al. [9] introduced a simplified Excel template that uses queueing theory to determine the optimal number and scheduling of maintenance service teams for a fleet of ships, providing an accessible approach to complex scheduling challenges. Heuristic optimisation methods have also proven effective in resource allocation for maritime operations. Boudreault et al. [10] applied Constraint Programming (CP) with a Solution-Based Phase Saving (SBPS) heuristic to optimise resource allocation in ship refits, achieving improvements in project duration, resource utilisation, and robustness over traditional heuristics. Cao et al. [11] introduced the Chaotic Quantum Sparrow Search Algorithm (CQSSA) to reduce ship port time, transportation distance, and waiting time, outperforming conventional methods. However, CQSSA is sensitive to initial parameter settings and may converge prematurely, while CP struggles with scalability and continuous variables [10], [11]. Verstichel & Vanden Berghe [12] developed a discrete-event simulation model (DES) using MOGLi to simulate ship movements and lock scheduling, optimising waiting times and resource usage using a Mixed-Integer Programming solver. Hybrid simulation models have emerged as flexible tools to overcome limitations of traditional methods. Muravev et al. [13] proposed a hybrid model combining agent-based modelling (ABM) and system dynamics (SD) to optimise key parameters in an intermodal terminal. This model captures both micro-level agent behaviour and macro-level system dynamics but does not account for meso-level processes that may influence terminal operations. Mustafee et al. [14] demonstrated the scalability of hybrid models, starting from high-level models that require minimal data using SD and narrowing to detailed structures using DES or ABM. Similarly, Viana et al. [6] discussed the flexibility of hybrid models in adapting to parametric and structural changes, noting the limitations of traditional simulation models due to rigidity and simplified assumptions. Hybrid models allow complex systems to be divided into smaller, manageable subsystems, effectively capturing relationships and interdependence between various processes. In complex scheduling and resource allocation, hybrid optimisation methods provide adaptable solutions. Fontes et al. [15] combined Particle Swarm Optimisation (PSO) with Simulated Annealing (SA) for job shop scheduling, line balancing, and stacking sequence design. This method leverages PSO's strength in exploring solution spaces and SA's ability to avoid local optima. Similarly, Lin & Ying [16] and Katsigiannis et al. [17] used a hybrid of SA and Tabu Search (TS) to improve solution quality in non-permutation flowshop scheduling and small autonomous power systems operations, respectively. These methods balance SA's faster convergence with TS's neighbourhood search capacities. However, while hybrid approaches address limitations of individual optimisation methods, they may still get trapped in local optimal and often require more computational time than single algorithms, due to sequential execution [16].

The literature review reveals that studies on resource scheduling and utilisation in ports often overlook the complexities of facility assets like docks and berths. While extensive research has focused on the berth allocation problem, dock allocation, which carries greater cost implications, receives notably less attention. Research on dock schedule forecasting, resource allocation, and long-term investment planning remain underexplored. Furthermore, although hybrid optimisation research has demonstrated the advantages of combining algorithms, few studies apply these methods to multi-objective optimisation for cost reduction in port facilities. Existing resource allocation studies tend to prioritise efficiency over cost optimisation. This study addresses these

gaps by proposing a methodology that accelerates dock resource allocation requiring additional expenses to maintenance which enable reduction in ship idle time and costs.

3. Methodology

As shown in Figure 1, the approach used for this problem majorly focused on building a hybrid simulation model using ABM-DES (Agent Based Modelling and Discrete Event Simulation) to build in the port complexities. The hybrid model simulates interactions between ship and port assets using agents to capture characteristics, considering factors like ship variability, maintenance capabilities and potential outages. It uses discrete event simulation to handle maintenance events at the port, ensuring well-defined and time-sequenced execution of tasks and resource management. The hybrid model using bottom-up approach to embed meso level in the architecture in the form port resource downtimes and compatibility to ship class complexities whereas the macro level represents the maintenance and at the micro level the docking and berthing activities. Further the cost optimisation experiments determine the reduced ship maintenance durations making vessels available faster for operations.

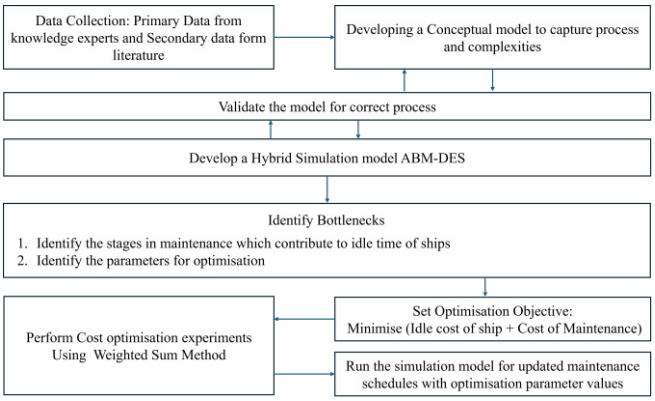


Fig. 1: Methodology used to develop maintenance schedules by reducing idle period of assets through cost optimisation.

The model validation goes through conceptual model validation which uses iterative process involving creation of model, validating it with experts for accuracy, and refining it based on received feedback [18]. Once the conceptual model is validated, it is used to create a software model which is then verified using Static and Dynamic approaches. Finally, Operational validation is performed which refers to the process of testing the entire model to assess its effectiveness in serving its intended purpose of creation [18]. The simulation model is studied to understand the stages which create bottlenecks in the maintenance process and identify the parameters that needs to be optimised. This methodology performs cost optimisation to find the investment in the maintenance cost which will bring the idle cost of ships to minimum. The increase in maintenance cost will fasten the maintenance activity and free the dock faster which can then accommodate the idled ship sooner. Since, both the idle and maintenance costs are conflicting costs the challenge lies in finding the balance. For optimisation, the weighted sum method is employed initially to unify multiple costs into a single minimization objective, streamlining optimisation efforts towards a composite objective function [19]. The weighted sum method is used to find the minimum optimal point (non-dominated solution) on the Pareto optimal set by combining costs and minimizing the aggregated sum of the objective functions as denoted below [19].,

$$U = \sum_{i=1}^{k} w_i * F_i(x) \quad (1)$$

where U is the weighted aggregated sum of all the objective functions to be minimized, w represents the scalar weight representing importance or priority of respective function relative to other, F denotes the objective functions, k are the number of objective functions and x are the parameters for optimisation. Different trade-off experiments for relative weights from 0 to 100% are performed and the weights are determined for the optimisation objective (equation 1). These cost optimisation experiments with the docking duration as parameters provide the optimal set of durations that satisfy the objective of minimizing the total cost. This optimal docking durations are fed to simulation model to get the updated maintenance schedules having better operational availability. The paper tries to create predicted maintenance schedules by cost optimisation and determine the minimum maintenance cost required. By investing in the dock maintenance, the docking duration can be reduced which can further free the dock resource faster and undertake the maintenance of ship faster. This will make ships available faster for operations and reduce the idle costs incurred by business.

4. Case Study

In its lifetime the ship goes through different phases such as Design, Construction, Operation, and Scrapping [20]. The ship's lifecycle comprises four phases: Design, where factors like fuel efficiency, transportation performance, and safety are prioritized for the vessel's operational lifespan; Construction, focusing on building the ship while minimizing environmental emissions; Operation, involving the ship's active period, including maintenance, upgrades, and repairs, with two maintenance types—Major Maintenance Period (MMP) and In-Commission Maintenance (ICM); and Scrapping, where, upon reaching its No Operation Date (NOD), the ship undergoes fuel extraction, dismantling, and recycling. This study focuses on MMP. It is a maintenance activity happening between two commissions of a ship. It can be defined as a certification, without which a ship cannot sail and is carried out in 3 stages of Initial Berthing, Docking and Final Berthing as shown in Figure 2. The scope of the research limits the process under study to maintenance (MMP) and does not consider other activities such as Disposal and ICM (In-Commission Maintenance). The study also does not consider the human resources involved and the uncertainties that may arise to the arrival time of ships due to weather conditions.

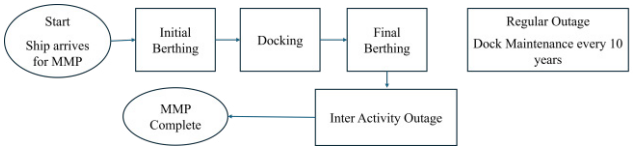


Fig. 2: MMP activity sequence close to real-world scenario after discussion.

4.1. MMP Complexities

The docks can only equip one ship at a time for maintenance, hence it is important to check dock capacity and compatibility for the ship asset coming for MMP else multiple ships may get queued at docks creating bottlenecks in the model. By continuously checking available dock capacity through Event trigger element this is resolved. The port complexities in the simulation model for dock allocation involve variability in ships called classes, the compatibility of docks for the classes of ship they can take in. The docks have their own maintenance performed at regular intervals called RO (Regular Outage) and IAO (Inter Activity Outage) required after every docking activity for the ship. The RO is performed every 10 years for 52 weeks. The IAO duration can be either 10 weeks or 20 weeks, depending on whether the previous class of ship is the same or different, respectively.

4.2. Hybrid Modelling ABM-DES

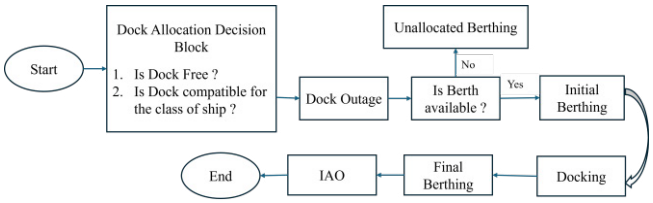


Fig. 3: Conceptual model for MMP.

The ABM-DES model is built using AnyLogic software version 8.2. It combines object-oriented visual tools with Java code to create integrated model that can be further customized [21]. The model inputs are shown in the Table 1. As illustrated in Figure 3, certain assumptions include the use of an 'Unallocated Berthing' resource in the model, which has infinite capacity to handle berthing activities when no berth is available during maintenance. Additionally, all berths and docks are assumed to be unoccupied at the start of the simulation.

Table 1. Simulation model inputs.

Model Inputs	Description
Ship Arrival Date	The date of Maintenance (MMP) for ship in its Lifecycle.
Berth/Dock Count	Number of Berths/Docks available for Maintenance at the start of simulation.
Ship Class	Ships are categorized into various classes, each class having its own dimensions. Thus, it depends on the class of ship if a dock can fit the ship or not.
Berth/Docking Time	The duration of berthing/docking activity. The berthing activity times are different depending upon the stage of Maintenance.
Commission Length	The length of ships commission after which it must perform mandatory maintenance.
Outage	Docks must undergo maintenance before they can undertake any ship for docking. This maintenance is Outage (RO and IAO).

4.3. Model Validation

The model validation is performed through 3 steps of Conceptual Model Validation, Computerised Model Verification and Operational Validation. The tests followed to validate conceptual model were Face Validity and Traces [18]. For Face Validity, the process expert was involved throughout the conceptual model development. For Traces test, the maintenance process is checked if it is followed correctly, by tracing the scenario if decision blocks lead vessel to correct dock. The conceptual model once validated, it is used to create a software model which is verified using Static and Dynamic approaches [18]. Static testing involves the test carried out before running the simulation such as, checking correct programming practices e.g., use of functions for repetitive code etc. Dynamic testing involves testing the model for different values and if the output is as expected. The tests followed are, checking if the MMP activities duration for different class of ships from simulation output is the same as input, Event Validity to check, if the MMP activities takes place in sequence of Berthing, Docking and Berthing, if the dock undergoes IAO after every docking activity and RO takes place at regular intervals.

4.4. Cost Equations and Determining weights

For cost optimisation the total cost which is the sum of idle and maintenance cost should be minimized. The idle cost to maintain ship out of water and the lost operation costs about 10000 GBP/day.

$$Cost\ of\ Idle\ Time = 10000I \tag{2}$$

where, I is the Idle period in days. The Cost of Maintenance is combination of cost required to perform maintenance for dock and idle or no operation cost of ship, given as below:

$$Cost\ of\ Maintenance = Maintenance\ costs + Idle\ Costs = \frac{28M^2 - 57LM + 30L^2}{ML} * 10000L + 10000M \tag{3}$$

where L is the standard MMP duration (with default docking periods for ship classes), M is the new MMP duration (with varying docking periods within a range for optimisation). The maintenance cost in equation 3 is derived from primary data provided by industry sources and validated by subject matter experts. Substituting equations 1 and 2 in equation 3 and dividing by 100 for simplicity, we get the objective function for cost optimisation.

$$\text{Minimise f(x)} = w_1 * \left(\frac{28M^2 - 57LM + 30L^2}{ML} * 100L + 100M\right) + w_2 * 100\text{I} \tag{4}$$

where I is the idle period, L is the standard MMP duration and M is the varying MMP duration, with values in days for the optimisation range. The objective function (equation 4) set for optimisation tries to minimize the total cost due to idle ships and dock maintenance. By using weighted sum method different relative weight combinations (from 0 to 100%) for equation 4 are carried out to explore different trade-offs between the conflicting costs [22].

4.5. Cost Optimisation

This study's optimisation problem aims to minimize ship idle time and maintenance expenses concurrently. The challenge lies in finding the balance in increased maintenance costs with decreased waiting time. The study addresses this dilemma through a unified cost optimisation experiment using OptQuest solver. The OptQuest optimiser combines several algorithms to find optimal solutions efficiently. It starts with Scatter Search to generate diverse solutions, followed by an LP (Linear programming) Feasibility Test to ensure solutions meet constraints. Tabu Search then refines these solutions by generating new ones while avoiding recently used points. A Restarting Strategy maintains diversity by mixing high-quality and new points. The Adaptive Memory and Age Strategy enhances the appeal of older, high-quality points. Finally, a Neural Network Accelerator predicts and avoids poor solutions, speeding up the search process. Together, these methods outperform traditional algorithms in accuracy and efficiency [23]. The experiment will provide the cost required to complete maintenance faster and thus free dock faster for the idled ships and complete maintenance faster making ship available for operations. The optimisation experiments are performed with the objective shown in equation 4. The parameters are docking duration with a range provided by discussing with experts as shown in Table 2.

Table 2. Optimisation parameters setup.

Ship Class	Type	Range (Weeks)	Step (Weeks)
A (Alpha)	Discrete	240-250	1
B (Beta)	Discrete	230-240	1
C (Gamma)	Discrete	165-175	1
D (Delta)	Discrete	100-110	1

Table 3. Trade-off experiments with different relative weights

Optimisation Objective weights (Minimise Total Cost = w1*Idle Cost + w2*Maintenance Cost)	Optimal Docking Periods (A, B, C, D = Class of ship) (Weeks)	Total Minimised Cost with optimal docking durations (GBP)
w1=w2=1	A-249, B-139, C-165, D-109	81,30,889
w1=0, w2=1	A-249, B-139, C-174, D-109	83,21,089
w1=0.1, w2=0.9	A-248, B-139, C-174, D-109	82,03,139
w1=0.2, w2=0.8	A-248, B-139, C-174, D-109	82,03,139
w1=0.3, w2=0.7	A-248, B-139, C-174, D-109	82,03,139
w1=0.4, w2=0.6	A-249, B-139, C-165, D-109	81,30,889
w1=0.5, w2=0.5	A-249, B-139, C-165, D-109	81,30,889
w1=0.6, w2=0.4	A-249, B-139, C-165, D-109	81,30,889
w1=0.7, w2=0.3	A-249, B-138, C-165, D-109	81,33,479
w1=0.8, w2=0.2	A-244, B-136, C-166, D-109	81,55,334
w1=0.9, w2=0.1	A-244, B-136, C-166, D-109	81,55,334
w1=1, w2=0	A-243, B-130, C-166, D-101	84,19,654

The experiments in Table 3 show that when the objective is to have minimum total cost it can be achieved at nearly equal weights and provide the optimal docking parameter values. It also provides a view into other experiments to understand when one cost reduction is favored more what will be the effect on the other. Figure 4 shows the idle and maintenance costs obtained from simulation runs with optimal docking durations for the different experiments from Table 3.

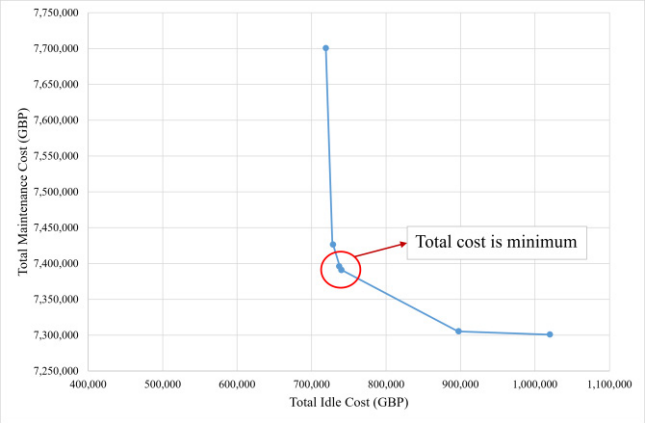


Fig. 4: Plot of Idle Vs Maintenance cost for the optimal docking values obtained from experiments in Table 2.

4.6. Results

As a result of optimisation the most optimal docking durations are obtained which when fed to simulation model provide the reduced idle period in ships as shown in Figure 5. It is observed that by increasing the maintenance costs by 1.525% the idle costs can be reduced by 45.2%.

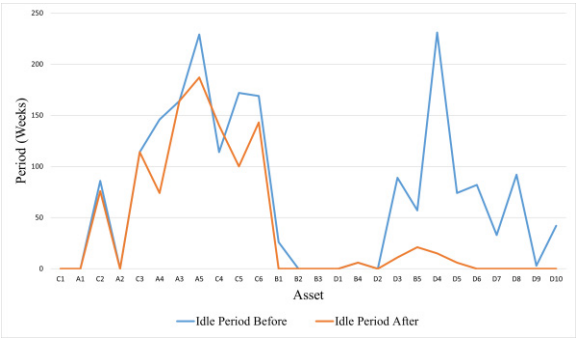


Fig. 5: Change in Idle period of ships (weeks) after optimisation.

Due to the reduced idle period as denoted by the red block in Figure 7, the overall MMP duration is shortened and the schedules of berthing and docking in MMP are updated.

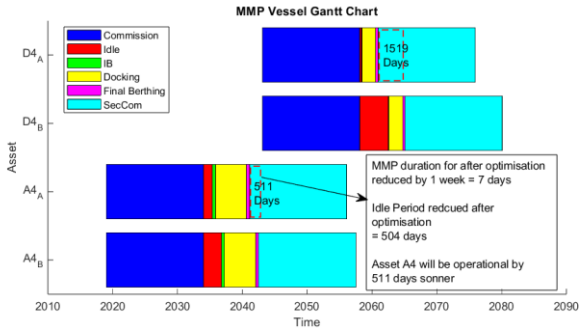


Fig. 6: Shows sample of MMP activities for ships with reduced waiting period after optimisation.

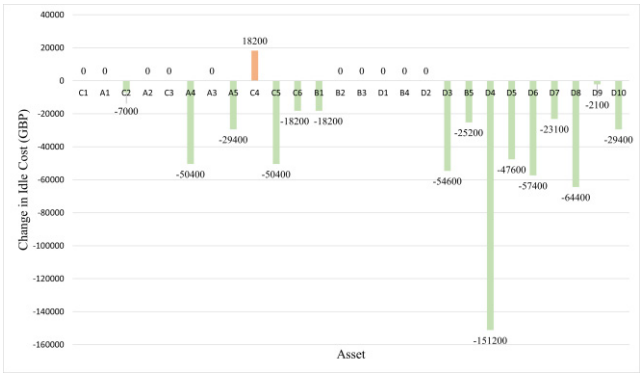


Fig. 7: Change in Idle Cost of ships after optimisation.

Table 4. Idle period and cost saved after optimisation.

	Total Idle Period (weeks)	Total Idle Cost (GBP)
Before Optimisation	1929	1350300
After Optimisation	1057	739900
Total Saved	872	610400

5. Conclusion

In contrast to the existing studies, the hybrid optimisation using OptQuest with a neural network backend, offers substantial benefits for cost optimisation. The idle time reduction is 45% compared to 15% of Tian et al. [7], but comes at the 1.5% increase in maintenance cost. The significant reduction in idle time makes ships more operationally available saving costs bared each day the ship is not available. The incorporation of dock downtime and compatibility with ship complexities in the model developed in this research has not been previously explored in ship maintenance studies [7], [8] and hybrid simulation models using ABDES (Agent Based Discrete Event Simulation) [13]. However, the methodology simplifies maintenance costs by applying uniform values across all ships of the same class which may not fully reflect the varying resource demands associated with the lifecycle of each ship. It primarily focuses on maintenance, without considering the influence of other port activities that might compete for the same resources. Future work can incorporate Lifecycle Cost Analysis (LCCA) to enhance the methodology by providing a more comprehensive understanding of long-term costs related to ship condition and port resource lifecycles, thereby identifying additional expenses over time to better understand the trade-off between maintenance and saved idle costs of ship.

Acknowledgements

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Cost Optimisation to determine ship maintenance schedules for improved operational availability

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