

AN INITIATIVE-BASED MILP APPROACH FOR SUSTAINABILITY PORT PERFORMANCE

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ABSTRACT

Purpose:

This study aims to develop a performance evaluation model tailored for Malaysian ports that addresses the limitations of existing global frameworks. While ports are crucial to trade and economic growth, their operations pose environmental challenges, including emissions, pollution, and habitat loss. Sustainable port initiatives are increasingly adopted to address these concerns, but existing performance measurement models often require extensive data and are not suited for localized application. This study seeks to provide a simplified, initiative-based model to assess sustainability performance efficiently and effectively within the Malaysian context.

Design/methodology/approach:

A Mixed Integer Linear Programming (MILP) model was formulated to assess port sustainability based on actual initiatives documented in annual reports from several major ports in Malaysia for over two years. Thematic analysis was used to categorize the initiatives into sub-factors under four core functions: landlord, regulatory, operator, and community. The MILP model incorporated an iterative optimization process involving four weightage scenarios and 100 iterations each, to determine the optimal configuration that maximized the sustainability score (Z), ensuring statistical robustness and relevance to operational realities.

Findings:

The Operator Function (OF) contributed most significantly to sustainability performance ($Z_3 = 1.126$), followed by the Landlord Function ($Z_1 = 0.487$), Regulatory Function ($Z_2 = 0.426$), and Community Function ($Z_4 = 0.292$). Despite expert consensus on the importance of infrastructure and long-term environmental planning (LF), ports allocated fewer initiatives to these areas. A clear misalignment was observed between expert-recommended priorities and the actual focus of port operations, with short-term efficiencies prioritized over long-term sustainability goals.

Research limitations/implications (if applicable):

The study focuses on selected ports over a limited timeframe, which may constrain generalizability. Future research should include multiple ports and a broader data range for validation.

Practical implications (if applicable):

The model enables Malaysian ports to evaluate sustainability initiatives using readily available data, providing actionable insights for policy adjustments and strategic planning. It functions as a decision-support tool by quantifying the impact of various initiatives, allowing port authorities to prioritize efforts that yield the greatest sustainability benefits. Additionally, the model can be integrated into regular sustainability reporting and internal performance reviews, ensuring alignment with both national green policies and international environmental standards. Its simplified structure supports routine use without requiring extensive technical expertise or large-scale data systems.

Originality/value:

This study presents a novel, context-specific MILP model that balances simplicity and effectiveness, addressing the data-intensity and generality of conventional sustainability performance models.

Keywords: Sustainable ports, MILP model, Malaysia, performance measurement, port initiatives

Introduction

Ports play a vital role in global trade and economic development, but their operations often contribute to environmental challenges such as greenhouse gas emissions, water pollution, and biodiversity loss. To address these concerns, sustainable port initiatives have been introduced, supported by various performance measurement models designed to evaluate their effectiveness. However, most existing models are developed for broader global contexts, relying on numerous variables and demanding extensive data collection, which makes them less practical for localized applications. This is particularly true in regions like Malaysia, where unique operational and environmental conditions require a more tailored approach. This study introduces a Mixed Integer Linear Programming (MILP) model specifically designed for the Malaysian port scenario, prioritizing simplicity, efficiency, and contextual relevance. By focusing on readily available data, the model streamlines the evaluation process without sacrificing accuracy, offering direct assessments of sustainability initiatives implemented by port authorities (Acciaro et al., 2014). It integrates landlord, regulatory, operational, and community-oriented factors to provide a holistic view of sustainability performance, highlighting both strengths and areas for improvement. Unlike conventional frameworks, its initiative-based structure ensures actionable insights that align with Malaysia's regulatory and operational context while maintaining compatibility with global environmental goals. Ultimately, the MILP model bridges the gap between complexity and practicality, serving as an effective tool to enhance sustainability strategies in Malaysia's ports.

A Multisectoral Review of MILP Applications with a Focus on Sustainable Port Operations

MILP has been widely used as a robust optimization technique in many sectors such as logistic, energy, and industrial planning. This technique particularly valued for its ability to handle complex decision-making problems. For example, Ronchi et al. (2025) developed a MILP model to optimize quality inspection in multi-product systems by combining different technologies and constraints such as the availability of workforce and the accuracy of detection. Similarly, Wierzbowski et al. (2016) came up with eMix MILP to help national power systems find the best long-term energy mix optimization. This model incorporated both operational reserves and policy driven target which demonstrate that MILP can take into account both strategic and daily operational needs while ensuring computational ability for large-scale planning tasks. In the context of distribution networks, Jooshaki et al. (2019) proposed an MILP formulation that included reliability indices in the planning of infrastructure expansion. This model uniquely included reward-penalty systems for reliability performance which helped to align with economic and sustainability goals.

In port operations, MILP models have been useful for improving a wide range of port operations ranging from berth to energy management. For example, Pereira et al. (2025) developed a MILP model to improve the efficiency of berth and stevedoring at Port of Leizoes by minimizing the vessel waiting times and its operational delays, thus it will lower the port emission and helps port to meet global sustainability goals. Iris and Lam (2021) also suggested a MILP model for smart ports to integrated both operations and energy management under uncertain renewable energy generation. The model required detailed infrastructure inputs, such as cold ironing, crane usage, and energy pricing mechanisms, to balance operational efficiency with environmental goals.

However, a notable limitation of traditional MILP application is that it needs large, detailed datasets such as real-time operational data, long-term projections, or full inventories of assets and technology configurations (Gabielli et al., 2017). Thus, this makes it harder to use in smaller or less-developed areas where detailed data may not be available. In response to these challenges, this study intentionally designed a simpler MILP model for Malaysian ports by using readily available initiative data and expert-based weights. This approach makes it more practical for localized deployment where detailed environmental or operational datasets might be scarce or inconsistent. It shifts the focus from high-resolution input modelling to practical initiative impact assessment, thus offering a strategic tool that is both scalable and locally implementable.

Methodology

This section outlines the step-by-step methodology employed in the study to evaluate and optimize the environmental sustainability performance of port initiatives. The approach integrates data collection, model formulation, iterative optimization, and validation to derive actionable insights for decision-making.

Data Collection and Preparation

Sustainability in ports requires coordinated action across multiple operational and administrative functions. Several key port functions can be identified as central to the implementation and monitoring of sustainability initiatives. Acciaro et al. (2014) identified four (4) core port functions from past studies: landlord, regulatory, operator, and community to be collectively essential for transitioning ports toward environmentally sustainable and resilient operations in their InnoSuTra EU FP7 project.

(a) Mapping Technique for Port Environmental Initiatives to Port Authority Function Dimensions

In order to map the environmental initiatives with port authority function dimension, the hybrid approach of thematic analysis and evidence-based justification were conducted. This hybrid approaches ensure that each initiative is systematically being mapped under the appropriate function while being supported by relevant academic research.

The first phase of mapping is using thematic analysis technique. Each initiative is interpreted as a thematic expression of one or more sustainability goals. Once the identifying purpose of each initiative is identified, then it will be matched to its specific port authority function dimensions. This matching is also based on the description and criteria of each dimension to ensure the allocation is conceptually aligned with the intended role and responsibility of that function. For example, initiatives focused on renewable energy installation or low-emission adoption such as “converted 100% of conventional light bulbs to LED alternatives”, “installed submeters to separate energy consumption” and “Adding IoT power meters to each floor and chiller” are thematically linked to the “Operator Function” dimension, specifically under sub-factors “improve energy efficiency and energy conservation within the port. Similarly, initiatives related to policy creation, air quality monitoring, or regulatory compliance, such as “pollution control monitoring”, and “zero-tolerance for suppliers’ human rights violations, circularity, and waste reduction in the supply chain” are categorized under “Regulatory Function”.

Next, the second phase of mapping involved evidence-based validation process which to ensure that the mapping of environmental initiatives is not only conceptually sound but also matched with actual operational practices. The analysis involved systematic integration of academic literature to support and validate the thematic classification established in the first phase. This evidence-based validation serves as an essential external check to confirm each mapping decision through empirical research and scholarly literature. For each mapped initiative, relevant academic research is cited to support the rationale for the chosen dimension. The literature was reviewed beyond providing background information, but for specific examples where similar initiatives were either discussed, evaluated, or implemented under the scope of one of the port authority functions. For example, if an initiative involved the electrification of port vehicles, it will be mapped to the “Operational Function – improve energy efficiency”.

(b) Case Study

The data for this study was collected exclusively from real world data to ensure the relevance and practical applicability of the findings. Data was obtained from the annual reports from Northport Sdn Bhd over a two-year period. These reports provided detailed information on the initiatives undertaken by the port (MMC, 2022). The focus on real world data ensures that the results are grounded in the actual practices and operational priorities of Malaysian ports. The initiatives documented in the annual reports were categorized into sub-factors within each primary port function by using thematic analysis. For example, a total of ten (10) distinct initiatives were identified for the Landlord Function (LF) based on the annual reports from Northport Sdn Bhd. These initiatives were categorized under six sub-factors which respect to LF. For the first sub-factor which is protecting the port ecosystems (LF1), two (2) key initiatives were highlighted. The first initiative involves conducting annual water sampling analysis at port valuation points. This initiative plays a significant role in preserving the aquatic ecosystems within the port area and ensuring that biodiversity is sustained (Kraus, 2023). The second initiative involves the installation of oil and grease traps at all maintenance and repair workshops. These initiatives effectively prevent pollutants such as oil residues and grease from entering the water systems (Mong’ina, 2018).

Three (3) initiatives were identified for the second sub-factor which is creating optimal space allocation and green recreational areas (LF2). These include mangrove planting projects, reforestation efforts, and plans to reuse degraded materials for reclamation. Mangrove planting projects are instrumental in creating green recreational areas while also contributing to natural preservation (Primavera et al., 2019). Reforestation initiatives enhance biodiversity and expand green spaces, fostering environmental sustainability and urban green infrastructure (Alvarez, 2013). Additionally, the reuse of degraded materials for reclamation optimizes the use of available resources and reducing the need for new land development (Zhu et al, 2024).

The third sub-factor which is providing adequate waste reception facilities (LF3) also includes two (2) initiatives. The first focuses on scrap metal and wastepaper handling, which ensures that proper recycling and waste management facilities are available at the port. This initiative supports the port compliance with international waste management standards which contributes to both environmental sustainability and operational efficiency (Mohee et al., 2012). The second initiative is the incorporation of rainwater harvesting systems. By harvesting and recycling rainwater, the port effectively reduces its reliance on external water sources and contributes to sustainable resource utilization (Gupta et al., 2005). There is one initiative each for sub-factor to ensure the use of space is optimised in master planning (LF4), include environmental considerations in the planning and execution of connectivity policy and infrastructure (LF5), and adapt to climate change (LF6). The initiatives are reusing degraded materials for reclamation, installing submeters to separate energy consumed by the cranes etc, and completing climate change risk assessment, respectively. The same exercise was done for the remaining three port functions: regulatory function (RF), operator function (OF), and community function (CF), respectively.

Model Formulation

The model optimizes the number and distribution of sustainability initiatives based on expert weightage across all the sub-factors in the framework. The model calculates the total sustainability performance through the combination of initiative quantity and alignment with their sub-factors. The primary objective of the model is to maximize the overall sustainability metric, $Max Z$, which was formulated as:

Maximize sustainability score Z :

$$Maximize Z = \sum_{i=1}^4 \sum_{j=1}^{n_i} w_i \cdot g_{ij} \cdot x_{ij}$$

Where:

- Z : Overall sustainability metric
- n_i : Number of sub-factors under function i
- w_i : Fixed expert-determined weight for function i
- g_{ij} : Global weight of sub-factor j under function i
- \bar{x}_{ij} : Max number of possible initiatives under ij
- $i \in \{1, 2, 3, 4\}$ – Main functions:
- $j = 1, \dots, n_i$ – Sub-factors under each function
- $x_{ij} \in \mathbb{Z}_{\geq 0}$: Number of initiatives selected under sub-factor j in function i

Subject to the following constraint that ensures that the number of initiatives selected for each sub-factor remains within realistic and implementable limits:

$$0 \leq x_{ij} \leq \bar{x}_{ij} \quad \forall i, j$$

Where:

- x_{ij} , denotes the number of initiatives selected for sub-factor j under function i . This variable is the primary decision variable of the model, as it captures the port's level of implementation effort for each specific sustainability area.

- \bar{x}_{ij} represents the maximum number of initiatives available under sub-factor j in function i , based on the actual data collected from port documentation.

Iterative Optimization

To identify the optimal weightage configuration that maximizes Z , an iterative optimization process was conducted. This iterative optimization process serves several critical objectives, such as enhancing the robustness and reliability of the sustainability performance assessment model. Four (4) iterations were considered by systematically varying the weightages assigned to the four (4) main port functions, w_i , where the aim is to ensure that the final sustainability performance score is not dependent on arbitrary assumptions. The weightage of each port function has been calculated based on expert evaluations to be 0.298 for LF, and 0.281, 0.265, and 0.156 for RF, OF, and CF, respectively. For each iteration, one function weightage, w_i , is fixed while the remaining three are randomized under the constraint that the total must equal one. The randomization is repeated across 100 iterations thus allowing the model to explore a wide range of plausible configurations. This iterative process also calculates the maximum, mean, and standard deviation of the sustainability performance metric Z , to ensure the results are statistically stable and representative.

Analysis and Findings

The metric Z values were computed as the product of the global weight and the number of initiatives undertaken in respective sub-factors. For example, as shown in Table 1, a sub-factor that protects the port ecosystems (LF1) had a global weight of 0.064, and two initiatives were implemented by the port; the impact is calculated as $0.064 \times 2 = 0.128$. Note that Global Weights were calculated based on its priorities in previous research.

Table 1: Total objective function values (Z)

| Subfactor | Global Weights | Initiatives | Global Weights*Initiatives | Sum of Global Weights*Initiatives (Z) |
|-----------|----------------|-------------|----------------------------|---|
| LF1 | 0.064 | 2 | 0.128 | 0.487 |
| LF2 | 0.058 | 3 | 0.174 | |
| LF3 | 0.050 | 2 | 0.100 | |
| LF4 | 0.047 | 1 | 0.047 | |
| LF5 | 0.038 | 1 | 0.038 | |
| LF6 | 0.041 | 0 | 0.000 | |
| RF1 | 0.073 | 2 | 0.146 | 0.426 |
| RF2 | 0.060 | 3 | 0.180 | |
| RF3 | 0.061 | 1 | 0.061 | |
| RF4 | 0.048 | 0 | 0.000 | |
| RF5 | 0.039 | 1 | 0.039 | |
| OF1 | 0.105 | 4 | 0.420 | 1.126 |
| OF2 | 0.091 | 7 | 0.637 | |
| OF3 | 0.069 | 1 | 0.069 | |
| CF1 | 0.032 | 3 | 0.096 | 0.292 |

| | | | |
|-----|-------|---|-------|
| CF2 | 0.030 | 1 | 0.030 |
| CF3 | 0.025 | 2 | 0.050 |
| CF4 | 0.025 | 2 | 0.050 |
| CF5 | 0.022 | 2 | 0.044 |
| CF6 | 0.022 | 1 | 0.022 |

In each iteration, one weightage was fixed while the remaining three were randomized. Example of Iteration 1, when w_1 (LF weightage) is fixed, the weightage for $w_2, w_3,$ and w_4 are randomized to identify the configuration that yielded the highest Z . This process was repeated for w_2 (Iteration 2), w_3 (Iteration 3), and w_3 (Iteration 4). This randomization was constrained such that the sum of all four weightages always equaled 1. The fixed values of $Z_1, Z_2, Z_3,$ and Z_4 were then multiplied by their corresponding weightages to calculate the overall sustainability performance ($Max Z$). Table 2 shows the results of 100 iterations when the weightage of LF is fixed at 0.298 and when the weightage for RF, OF, and CF are fixed at 0.281, 0.265 and 0.156, respectively.

Table 2: Result from Iterative Analysis

| Highest $Max Z$ | $w_1(Z_1)$ | $w_2(Z_2)$ | $w_3(Z_3)$ | $w_4(Z_4)$ | $Max Z$ | Mean | Std.Dev |
|---------------------------|------------|------------|------------|------------|---------------|--------|---------|
| When w_1 fixed at 0.298 | 0.1451 | 0.1188 | 0.2932 | 0.0475 | 0.6047 | 0.4801 | 0.0700 |
| When w_2 fixed at 0.281 | 0.1390 | 0.1197 | 0.2749 | 0.0553 | 0.5889 | 0.4732 | 0.0599 |
| When w_3 fixed at 0.265 | 0.1450 | 0.1099 | 0.2984 | 0.0523 | 0.6056 | 0.5649 | 0.0208 |
| When w_4 fixed at 0.156 | 0.0101 | 0.0023 | 0.9210 | 0.0456 | 0.9789 | 0.8154 | 0.0774 |

In summary, this iterative optimization helps to identify the optimal weightage distribution that maximizes the sustainability performance. This approach can guide the decision-makers on most effective strategic focus by examining the configuration of which weights yield the highest score. Based on the finding, it clearly shows that the operator function (OF) has the highest potential impact with the maximum Z score of 0.9789 achieved when OF weightage set at 0.9210. Finally, this result shows the immediate effectiveness of operational measures in achieving environmental sustainability in port operations.

Conclusion and Recommendations

The study analysed the contributions of port initiatives to sustainability performance by compiling the number of initiatives undertaken in each sub-factor and applying global weights to calculate their respective impacts. These impacts were then aggregated within each main function to assess their total contribution to the overall sustainability performance metric (Z). For example, OF2 is a sub-factor under the OF was observed to have the highest number of initiatives of seven (7), which significantly contribute to Z_3 with a weighted value of 0.637 (calculated as 0.091×7). This highlights the operational focus of the ports in enhancing day-to-day efficiencies.

The total contribution of each function was obtained by summing the weighted contributions of all its sub-factors. This aggregation provided a clear picture of how each factor influenced the overall sustainability metric (Z). The analysis of sub-factor contributions is vital as it provides actionable insights into the performance and alignment of port initiatives with sustainability goals. This analysis helps to identify which areas are performing well and which are underperforming. For example, if a particular sub-factor under the OF has a high number of initiatives and significant contributions, it demonstrates that operational efficiency is being prioritized. Conversely, if a sub-factor under the LF exhibits a low contribution and number of initiatives, it suggests that infrastructure related initiatives may be neglected in achieving overall

environmental sustainable port. This evaluation highlights areas where efforts or resources need to be increased or realigned to improve overall performance.

Another critical aspect of this analysis is its ability to assess whether current practices align with broader strategic objectives. Ports often operate within sustainability frameworks that prioritize certain functions such as infrastructure resilience or regulatory compliance. For instance, if experts identify the LF as the most critical for environmental sustainability but the analysis reveals a higher contribution from the OF, it indicates a misalignment between expert recommendations and actual practices. This insight allows decision makers to realign their initiatives to better reflect strategic priorities and long-term goals.

In addition, the analysis supports policymakers and port authorities by providing data driven insights for effective policy formulation and resource allocation. A detailed breakdown of performance across main functions and sub-factors allows decision-makers to identify areas that require further investment or policy intervention. For example, underinvestment in infrastructure, community or regulatory compliance can be addressed based on the evidence provided by the analysis. This ensures that policies and decisions are grounded in real world data and tailored to address specific weaknesses in the port sustainability strategy.

Furthermore, the analysis establishes benchmarks for continuous improvement by repeating this process annually or after significant changes, ports can monitor improvements in underperforming sub-factors, evaluate the impact of newly implemented initiatives, and refine their strategies for enhancing overall performance. It also supports transparent communication with stakeholders such as governments, investors, and the community by quantifying the impact of initiatives. This transparency builds trust and can secure funding or support for future projects.

Besides, this analysis is also essential for guiding policy formulation and decision-making. It provides a comprehensive understanding of the contributions of various functions and sub-factors by enabling ports to refine their sustainability strategies. Moreover, the evaluation serves as a benchmark for continuous improvement. By periodically reassessing priorities and reallocating resources, port can monitor progress, track the effectiveness of newly implemented initiatives, and ensure that sustainability objectives are met over time.

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