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Systematic Literature Review of GPS-based Multi-Objective Environmentally Friendly Shortest Path with a Proposed Lexicographic Framework

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Abstract

Environmentally friendly path planning has become an important topic in transportation research as concerns about carbon emissions continue to grow. This study presents a Systematic Literature Review (SLR) and bibliometric analysis to identify the state of the art in green shortest path optimization. Using the PRISMA guideline, the study analyzes 20 articles selected from Scopus, ScienceDirect, and Dimensions databases published between 2021 and 2025. Results indicate that the field is dominated by metaheuristic and AI-based approaches, while deterministic methods with explicit objective prioritization remain underutilized. Bibliometric visualization identifies traffic congestion and carbon emission policies as major research clusters, yet few studies integrate these with real-time GPS data in developing countries. Based on these findings, this paper proposes a conceptual framework for a GPS-based Lexicographic Multi-Objective Optimization model. The proposed framework prioritizes carbon emission minimization as the primary objective, followed by travel time, offering a transparent decision-making tool for sustainable urban transportation.

Keywords: Green Shortest Path; Multi-Objective Shortest Path Problem; Lexicographic Method; Systematic Literature Review; Bibliometric Analysis.

1. Introduction

The problem of determining the optimal shortest path has long been a fundamental subject in operations research and graph theory [1]. Land transportation networks can be modeled as graphs, where intersections or key locations are represented as vertices and road segments as edges. This graph-based representation enables systematic analysis of network topology and performance and has been widely applied in transportation optimization studies [2]. In practical routing problems, multiple and often conflicting objectives arise, such as minimizing travel time while reducing carbon emissions, leading to the formulation of the Multi-Objective Shortest Path Problem (MOSPP) [3]. Addressing this problem requires optimization approaches that can handle trade-offs between competing objectives in a structured manner [4]. Among the available approaches, the Lexicographic Method is particularly suitable when there is a clear priority among objectives, for example when environmental considerations are placed above operational efficiency [1, 4, 5].

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In recent years, research on environmentally friendly or green shortest path problems has expanded significantly through the application of metaheuristic algorithms [6–8] and machine learning-based approaches [9]. While these methods are effective in exploring large solution spaces, their implementation often depends on extensive data availability and high computational requirements. Such conditions can be challenging in urban transportation networks characterized by heterogeneous traffic and limited data quality, which are common in many developing countries [10]. Consequently, there remains a need for optimization frameworks that are robust, transparent, and less dependent on complex data structures. In this context, deterministic approaches such as the Lexicographic Method offer advantages by providing hierarchical solutions with explicit objective prioritization.

The transportation sector is widely recognized as a major contributor to global carbon dioxide (CO_2) emissions. In many developing countries, rapid urbanization, increasing private vehicle ownership, and persistent traffic congestion have intensified emission levels in urban road networks [11, 12]. These conditions not only increase fuel consumption and travel time but also pose challenges to achieving long term climate mitigation targets, such as net zero emission goals [13]. Therefore, incorporating environmental objectives into route optimization is increasingly important for the development of sustainable transportation systems.

Given this background, a systematic review that maps the development of research on eco-friendly shortest path optimization is necessary. This study aims to review the state of the art in carbon emission-based shortest path optimization using a multi-objective approach and to identify existing research gaps that can support the formulation of a priority-based optimization framework. To address these objectives, this study is guided by the following research questions:

1. Which optimization methods are used in the environmentally friendly shortest path research field?
2. How is the state of the art in green shortest path optimization determined to formulate new research directions?

This paper contributes: (i) a comprehensive Systematic Literature Review (SLR) and bibliometric mapping of the field, (ii) an analysis of current methodological trends and gaps, and (iii) a proposed conceptual optimization formulation to be validated in future work.

2. Methods

This chapter outlines the research methodology employed in this Systematic Literature Review (SLR) study. The applied method combines a SLR approach with bibliometric analysis, alongside a conceptual study of GPS-based eco-friendly shortest path mathematical optimization models. This approach is utilized to map previous research developments, identify research gaps, and establish a conceptual foundation for developing Multi-Objective Optimization models within eco-friendly navigation systems.

2.1. Research Design

This study employs a SLR approach combined with bibliometric analysis to examine research developments regarding the determination of GPS-based eco-friendly shortest paths. The SLR approach was selected for its ability to provide a systematic, transparent, and reproducible literature search process, ensuring that the obtained review results are objective and structured [14]. The search was conducted to retrieve publications within the time window of 2021 to 2025, ensuring the review captures the most recent developments.

As the primary guideline for conducting the SLR, this study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) method [15]. PRISMA is used to ensure that every stage of literature selection, from identification to article inclusion, is conducted consistently and is welldocumented. Consequently, the risk of bias in literature selection can be minimized.

The research scope focuses on studies addressing shortest path optimization, Multi-Objective Optimization, eco-routing, and the utilization of GPS and road networks in navigation systems. Selected literature is then analyzed quantitatively through a bibliometric approach and qualitatively through a state of the art review. The results from this stage serve as a conceptual basis for formulating directions for developing shortest path optimization models that are not only efficient in terms of time or distance but also environmentally friendly.

2.1.1. Inclusion and Exclusion Criteria

To ensure the relevance and quality of the selected literature, specific inclusion and exclusion criteria were applied. These criteria are detailed in Table 1.

Table 1: Inclusion and Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
Published between 2021–2025	Published before 2021
Written in English	Non-English documents
Article type: Journal Articles and Conference Proceedings	Review papers, book chapters, and short surveys
Focuses on Multi-Objective Optimization or Green Shortest Path	Single-objective optimization (distance only)
Mentions GPS, real-time data, or dynamic traffic	Purely theoretical graphs without real-world data context

The research scope focuses on studies addressing shortest path optimization, Multi-Objective Optimization, eco-routing, and the utilization of GPS and road networks in navigation systems. Selected literature is then analyzed quantitatively through a bibliometric approach and qualitatively through a state of the art review. The results from this stage serve as a conceptual basis for formulating directions for developing shortest path optimization models that are not only efficient in terms of time or distance but also environmentally friendly.

2.2. Bibliometric Analysis

Bibliometric analysis is utilized in this study to obtain a quantitative overview of the structure and evolution of research in the field of eco-friendly shortest path optimization. This method leverages scientific publication data such as citation counts, keywords, authors, and inter article relationships to identify research trends and relationship patterns between topics [16].

According to Donthu et al. [17], bibliometric analysis is highly effective in mapping the development of a research field and uncovering both dominant and underexplored topics. In the context of this study, bibliometric analysis is used to identify how topics such as green shortest path, eco-routing, and Multi-Objective Optimization have evolved in recent years.

VOSviewer software is employed as the primary tool for bibliometric analysis due to its capability to visualize bibliometric networks intuitively and informatively [18]. VOSviewer enables the mapping of keyword relationships (keyword co-occurrence), citation relationships between articles, and author collaborations. Keyword co-occurrence analysis is used to identify research topic clusters, while overlay visualization is used to observe topic progression based on publication year.

The analyzed keywords include primary terms such as green shortest path, eco-routing, carbon emission, Multi-Objective Optimization, and GPS-based navigation. The results of this bibliometric analysis serve as the foundation for compiling the state of the art and identifying existing research gaps, particularly regarding the application of eco-friendly optimization models within the context of transportation in developing countries.

2.3. Mathematical Models and Formulations

This subsection presents the mathematical formulation that serves as the conceptual foundation of this study. The model integrates transportation network representation, carbon emission estimation, shortest path optimization, and multi-objective decision making using a lexicographic approach.

The transportation network is modeled as a directed graph $D = (V, A)$, where V denotes the set of vertices representing intersections or specific locations, and A denotes the set of directed arcs representing road segments [19]. Each arc $(i, j) \in A$ is associated with multiple attributes, namely distance d_{ij} (km), travel time t_{ij} (minutes), and estimated carbon emissions e_{ij} (g CO_2).

Carbon emissions are estimated using a simplified version of the MEET (Methodology for Estimating Emissions from Transport) model. For Euro I gasoline passenger vehicles with an engine capacity between 1.4L and 2.0L, the emission rate per kilometer $\varepsilon(v)$ (in g CO_2/km) is formulated as a function of average speed v (km/h) as follows [20]:

$$\varepsilon(v) = 231 - 3.62v + 0.0263v^2 + \frac{2526}{v},$$

this specific formulation for a speed range of 5-130 km/h [20]. The parameters include base emission constants, linear and quadratic speed components, and an inversely proportional term $(2526/v)$ which captures the significant increase in emissions during low-speed traffic or congested conditions [20]. For each arc (i, j), the total carbon emissions e_{ij} are calculated by multiplying the emissions rate with arc distance d_{ij} [20, 21]:

$$e_{ij} = \left(231 - 3.62v_{ij} + 0.0263v_{ij}^2 + \frac{2526}{v_{ij}}\right) \times d_{ij},$$

where v_{ij} denotes the average speed on arc (i, j) obtained from GPS-based traffic data. The shortest path problem on graph $D = (V, A)$ with source node $s \in V$ and destination node $t \in V$ is formulated as a network flow optimization problem [22]:

$$\begin{aligned}
\min \quad & \sum_{(i,j)\in A} c_{ij}x_{ij}, \\
\text{s.t.} \quad & \sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(k,i)\in A} x_{ki} = \begin{cases} 1, & \text{if } i = s, \\ 0, & \text{if } i \in V \setminus \{s, t\}, \\ -1, & \text{if } i = t, \end{cases} \\
& x_{ij} \in \{0, 1\}, \ \forall (i, j), (k, i) \in A,
\end{aligned}$$

where x_{ij} is a binary decision variable indicating whether arc (i, j) is included in the selected path, and c_{ij} denotes the cost associated with arc (i, j).

In eco-routing applications, travel time and carbon emissions constitute two conflicting objectives. Therefore, the problem is extended to a MOSPP [3], formulated as:

$$\begin{aligned}
\min \quad & [f_1(x), f_2(x)], \\
\text{s.t.} \quad & \sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(k,i)\in A} x_{ki} = \begin{cases} 1, & \text{if } i = s, \\ 0, & \text{if } i \in V \setminus \{s, t\}, \\ -1, & \text{if } i = t, \end{cases} \\
& x_{ij} \in \{0, 1\}, \ \forall (i, j), (k, i) \in A,
\end{aligned}$$

with objective functions defined as:

$$\begin{aligned}
f_1(x) &= \sum_{(i,j)\in A} e_{ij}x_{ij}, \\
f_2(x) &= \sum_{(i,j)\in A} t_{ij}x_{ij}.
\end{aligned}$$

To solve the MOSPP, a lexicographic optimization method is employed, prioritizing emission minimization over travel time [4, 5]. In the first stage, emissions are minimized:

$$\begin{aligned}
&\min\ f_1(x),\\
&\text{s.t.}\ \sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(k,i)\in A} x_{ki} = \begin{cases} 1, & \text{if } i = s,\\ 0, & \text{if } i \in V \setminus \{s,t\},\\ -1, & \text{if } i = t,\end{cases}\\
&\quad x_{ij} \in \{0,1\},\ \forall (i,j),(k,i) \in A.
\end{aligned}$$

Let the optimal solution be x_1^* with optimal emission value f_1^*. In the second stage, travel time is minimized while preserving the optimal emission level:

$$\begin{aligned}
&\min\ f_2(x),\\
&\text{s.t.}\ \sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(k,i)\in A} x_{ki} = \begin{cases} 1, & \text{if } i = s,\\ 0, & \text{if } i \in V \setminus \{s,t\},\\ -1, & \text{if } i = t,\end{cases}\\
&\quad f_1(x) = f_1^*,\\
&\quad x_{ij} \in \{0,1\},\ \forall (i,j)(k,i) \in A.
\end{aligned}$$

Travel time and emission parameters are derived from GPS-based traffic data, where $t_{ij} = d_{ij}/v_{ij}$ and emissions are computed using the MEET-based formulation. Speed data are obtained from the Google Maps API or similar sources, accounting for temporal traffic variations.

The proposed model is designed to be implemented using Python with PuLP for binary integer programming and NetworkX for graph representation. Validation is planned by comparing the eco-routing solution with shortest distance and shortest time routes. A reduction threshold of 5% is selected as a benchmark for sensitivity analysis to evaluate the trade-off between emission savings and increased travel time.

2.4. Bibliometric Mapping Methodology

The bibliometric mapping in this study is conducted through several structured stages to ensure comprehensive and scientifically accountable analysis results.

1. **Domain Determination**
   The domain under review encompasses shortest path optimization, eco-friendly transportation, Multi-Objective Optimization, and GPS-based navigation systems. This domain determination aims to bound the scope of research to remain relevant to the study's objectives [23].
2. **Scientific Database Selection**
   The databases used are Scopus, ScienceDirect, and Dimensions. These three databases were selected due to their extensive publication coverage and compatibility with bibliometric analysis using VOSviewer [24].
3. **Search Strategy Formulation**
   The search is conducted using a combination of keywords and Boolean operators. The article selection process follows PRISMA guidelines [15], which include identification, screening, eligibility assessment, and final article inclusion stages.
4. **Extraction and Cleaning of Bibliometric Data**
   Extracted article metadata includes title, abstract, keywords, publication year, author names, and journal sources. Data is then cleaned to remove duplicates and irrelevant articles.
5. **Analysis and Visualization using VOSviewer**

In this stage, a keyword co-occurrence network is constructed by setting a minimum threshold for keyword occurrences to ensure that the resulting visualization is representative and unaffected by rarely occurring terms [18].

6. **Interpretation and Synthesis of Bibliometric Mapping Results**
   The formed clusters are analyzed to identify main research themes, relationships between topics, and future research opportunities. The results of this analysis serve as the basis for compiling the state of the art and formulating the design of subsequent research regarding GPS-based eco-friendly shortest path optimization models.

3. Result and Discussion

This chapter presents the main results derived from the SLR process and bibliometric analysis concerning Multi-Objective Optimization for GPS-based eco-friendly shortest path determination. The analysis results are organized into several subsections, including keyword combination analysis, the PRISMA flow diagram, state of the art mapping, and bibliometric visualization using VOSviewer. All these findings are utilized to identify research patterns, methodological trends, and research gaps that form the basis of this study's contribution.

3.1. Keyword Combination Analysis

The analysis of keyword combinations was conducted to identify the interrelationships between the topics of Multi-Objective Optimization, shortest path determination, environmental aspects, and the use of the Global Positioning System (GPS) in transportation research. During the literature search process, keywords were classified into four main thematic categories, labeled A, B, C, and D, based on their research focus. The classification of keyword groups and their corresponding search terms is presented in Table 2.

Table 2: Keyword groups and corresponding search terms

Group	Theme	Keyword combinations
A	Multi-Objective Optimization	"Multi-objective optimization" OR "Multi-criteria optimization"
B	Shortest Path / Routing	"Shortest path" OR "Path optimization" OR "Eco-routing"
C	Environmental Impact	"Carbon emission" OR "Fuel consumption" OR "Energy-efficient"
D	Navigation System	"GPS" OR "Global Positioning System"

Combinations of these four keyword groups were systematically used to search for relevant publications in the Scopus, ScienceDirect, and Dimensions databases. A summary of the number of publications retrieved for each keyword combination is presented in Table 3, representing the initial search volume for each keyword combination prior to the screening process.

Table 3: Search Results based on Keyword Combinations

Type	Code	Scopus	ScienceDirect	Dimensions
I	A	2442	591	10993
II	B	903	1024	4283
III	C	4738	31794	62469
IV	D	818	9264	40867
V	BC	39	74	194
VI	AB	27	60	68
VII	ABC	2	19	12
VIII	ABD	0	6	1
IX	ABCD	0	2	0
Total types V to IX		**68**	**161**	**275**

The "Total types V to IX" row indicates the aggregated pool of potential articles identified through multi-keyword combinations (Codes V through IX) which served as the initial candidate set for the screening process. Based on Table 3, the combination of keywords B–C (shortest path and environmental impact) yields a relatively high number of publications across all databases. This finding indicates increasing research attention toward sustainable transportation and the environmental implications of road network–based navigation systems.

Conversely, keyword combinations that explicitly integrate Multi-Objective Optimization (Group A) with shortest path problems and environmental aspects (Groups B and C), particularly those involving deterministic solution approaches, remain very limited. Most existing studies rely on metaheuristic methods such as Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization to address the trade-off between travel time and carbon emissions.

The limited number of studies examining the application of deterministic methods, such as the Lexicographic Method, within the context of green shortest path problems reveals a clear research gap. This gap is particularly relevant because the lexicographic approach provides a structured hierarchical solution, which is well suited for decision making scenarios with strict priority objectives, such as minimizing carbon emissions as the primary goal and travel time as the secondary objective.

3.2. PRISMA Flow Diagram

The article selection process in this study is presented through the PRISMA diagram, which systematically illustrates the stages of identification, screening, eligibility evaluation, and article inclusion.

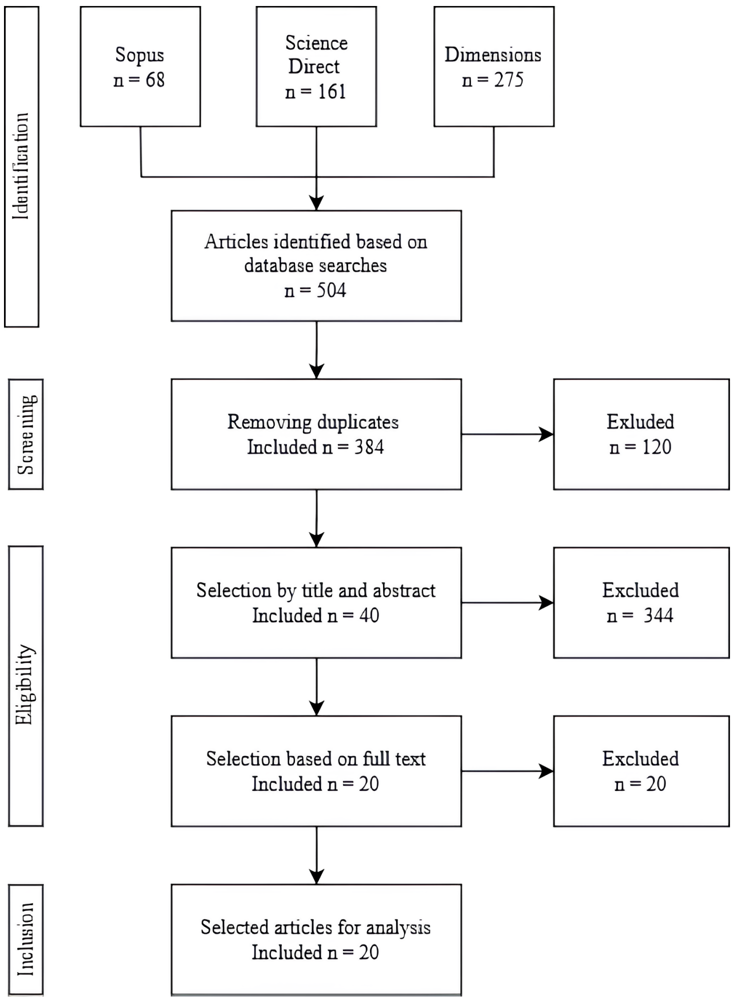


Fig. 1: PRISMA Diagram for Article Selection Process

The initial database search identified a total of 504 articles. After removing duplicates and screening titles and abstracts based on specific criteria, 45 articles were assessed for full-text eligibility. Finally, 20 articles met all inclusion criteria and were included in the qualitative and bibliometric analysis.

The selection results indicate that the majority of research still focuses on developed countries and transportation network contexts with traffic characteristics different from those in Indonesia. Following the screening phase based on titles, abstracts, and keywords, the number of articles decreased significantly due to duplication and topical irrelevance.

3.3. State of the Art

A summary of the state of the art from the selected studies is presented in Table 4.

Table 4: State of the art of Research Related to Green Shortest Path

No	Reference	MOO	Eco-Friendly	Shortest Path	GPS/GIS	Algorithm Used
1	Pradeep et al. (2024) [25]	–	✓	✓	✓	XGBoost
2	Elgammal (2025) [26]	✓	✓	✓	✓	MOPSO
3	Zhu and Zhu (2022) [27]	✓	✓	✓	–	NSGA-II, K-Shortest Path
4	Yang and Jiang (2024) [28]	✓	✓	–	–	ALNS–ACO
5	Li et al. (2022) [29]	–	✓	✓	✓	Dijkstra Variant
6	Saxena et al. (2025) [30]	✓	✓	✓	–	GNN + Dijkstra
7	Yang et al. (2023) [31]	✓	✓	–	–	Fuzzy Adaptive GA
8	Wu et al. (2024) [32]	✓	✓	✓	–	Modified DBO
9	Cheng and Jia (2024) [33]	–	✓	✓	–	GA-LNS
10	Benmessaoud et al. (2023) [34]	–	✓	✓	✓	Dynamic Graph-Based
11	Qi et al. (2024) [35]	✓	✓	✓	✓	Improved NSGA-II
12	Qian (2021) [36]	–	✓	✓	✓	Heuristic Algorithm
13	Yin (2025) [37]	–	✓	✓	–	Genetic Algorithm
14	Ren et al. (2025) [38]	–	✓	✓	–	Improved GA
15	Zhang et al. (2022) [39]	–	✓	✓	✓	Improved A*
16	Hu et al. (2023) [40]	✓	✓	✓	✓	Minimum-Snap Trajectory
17	Lu et al. (2023) [41]	✓	✓	–	–	NSGA-II
18	Ibrahim et al. (2022) [42]	✓	✓	✓	–	Optimal Transportation Theory
19	Xu et al. (2023) [43]	–	✓	✓	–	Dual-Subgradient
20	Kisialiou et al. (2024) [44]	✓	✓	✓	–	Dynamic Programming
21	Proposed Framework	✓	✓	✓	✓	Lexicographic Method

Based on Table 4, research on the green shortest path generally focuses on path optimization by considering carbon emissions, energy consumption, and travel time. The majority of studies have adopted a multi-objective approach, indicating increasing attention to sustainable transportation issues.

In terms of methodology, the most dominant approaches are metaheuristic algorithms and Artificial Intelligence-based methods, such as NSGA-II, Genetic Algorithm, Particle Swarm

Optimization, as well as combinations with Machine Learning and Deep Learning to enhance adaptability to dynamic traffic conditions. Quantitative analysis of the reviewed articles confirms this trend, revealing that approximately 70% of the studies rely on these metaheuristic or AI-based approaches. Furthermore, while variations of classic graph algorithms like Dijkstra and Dynamic Programming are used, they appear much less frequently as the primary optimization engine.

Nonetheless, most research still relies on Pareto solutions without explicitly setting goal priorities. The conflict between minimizing emissions and minimizing travel time is generally resolved through a compromise approach, rather than through a structured hierarchy of objectives.

From the implementation aspect, direct integration between optimization models and GPS-based navigation systems remains limited. Although 45% of the studies incorporate some form of spatial data or GIS, the direct utilization of real-time GPS speed data as a core dynamic variable in a deterministic optimization process has not been extensively studied in depth.

Moreover, the use of deterministic methods, especially the Lexicographic Method, is rarely found in the green shortest path literature. This is a missed opportunity, as this method offers the advantage of establishing clear priority between objectives, particularly when the environmental aspect is deemed more important than travel time.

In contrast to previous studies, this research proposes a Multi-Objective Optimization model based on the Lexicographic Method to determine the eco-friendly shortest path, with carbon emission minimization as the primary objective and travel time minimization as the secondary objective, integrated with the GPS. Thus, this study fills the gap between eco-friendly path optimization, deterministic goal prioritization, and implementation in real world navigation systems, especially within the context of Indonesian road networks.

3.4. Bibliometric Visualization

This subsection presents the bibliometric network generated through VOSviewer, based on keyword co-occurrence with a minimum threshold of two. This mapping reveals thematic clusters and conceptual linkages within the domain of the shortest path problem, carbon emission optimization, and dynamic programming.

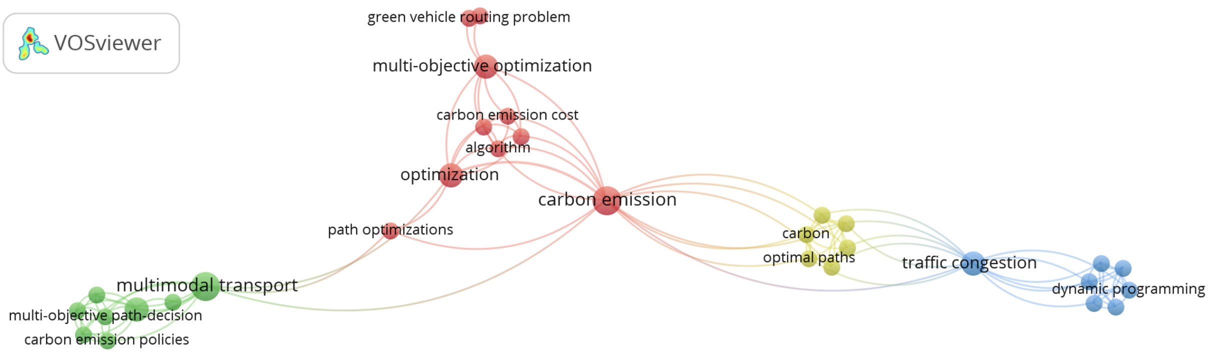


Fig. 2: The VOSViewer Bibliometric Visualization

The visualization highlights carbon emission as the most central and frequently appearing keyword, underlining its fundamental role in the field of green transportation optimization. The network reveals four thematic clusters, each representing a distinct research focus.

The first cluster (green) centers on carbon emission policies and multimodal transport, utilizing a systematic regulatory approach where environmental targets act as primary constraints. The second cluster (red) reflects a more adaptive and quantitative optimization, combining the shortest path problem, Multi-Objective Optimization, and carbon emission costs. The third cluster (yellow) focuses on the technical aspects of carbon management and traffic quality to better represent emission fluctuations. Finally, the fourth cluster (blue) advances risk management through mathematical transformation methods such as traffic congestion and dynamic programming, reflecting the increasing sophistication of decision-making models in modern green transportation systems.

The overlay visualization in Fig. 3 illustrates the evolution of research focus over time. In this mapping, the color gradient from dark blue to light yellow represents the progression of publication years, where blue nodes indicate earlier research focus, while light yellow nodes reflect newer developments. This visual pattern demonstrates how interest in specific topics has evolved, offering insight into emerging trends.

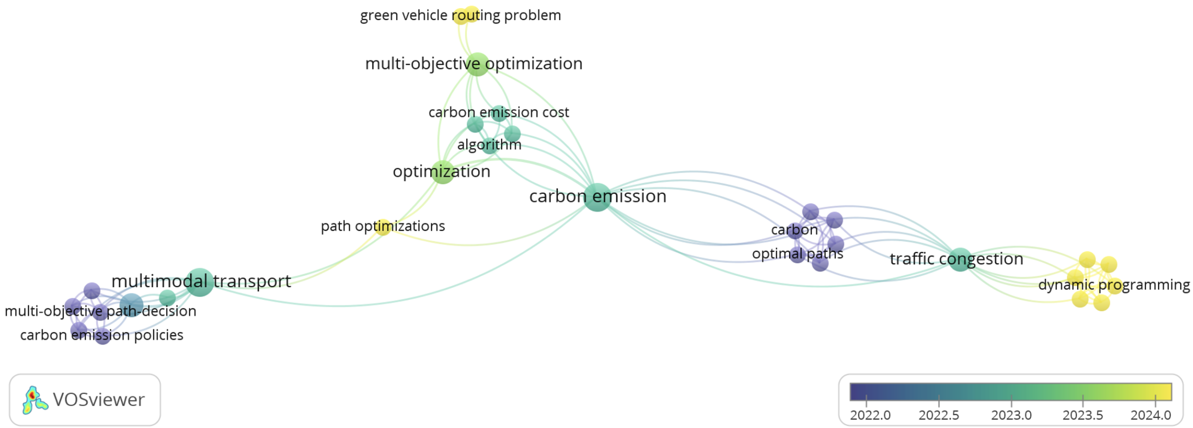


Fig. 3: The VOSViewer Overlay Visualization

Based on the bibliometric visualization map, the development of research in green transportation and carbon emission management shows a clear transition from classic frameworks toward more sophisticated and dynamic methodologies. In the early period (2022.0), studies concentrated on fundamental themes such as carbon emission policies and multimodal transport, establishing the groundwork for systematic path determination modeling and environmental risk assessment. During this phase, the emphasis was on relatively simple yet structured approaches.

Over time, research progressed toward Multi-Objective Optimization, indicating a growing interest in modeling uncertainty and the regulation of emission costs. In the intermediate period (2022.5–2023.0), attention shifted to optimization-based methods, aiming to improve the accuracy of emission estimation.

The most recent period (2023.5–2024.0) marks a prominent focus on optimal decision-making in complex environments, with traffic congestion and dynamic programming emerging as key themes. These approaches underscore the importance of strategic intervention to maintain transportation efficiency and prevent excessive emission increases.

Overall, the bibliometric trends illustrate a trajectory from static and deterministic models toward dynamic and data-driven frameworks. The insights derived from this analysis substantiate the structural design of the proposed mathematical model. Specifically, the prominence of traffic congestion within Cluster 4 necessitates the adoption of the MEET model, particularly its speed-dependent inverse term ($2526/v$), to accurately quantify emission surges during traffic delays. Concurrently, the thematic focus on carbon emission policies in Cluster 1 validates the preference for the Lexicographic method over Pareto-based approaches, as this hierarchical framework aligns with regulatory scenarios where environmental compliance functions as a non-negotiable constraint.

4. Discussion

Through a SLR and bibliometric analysis, clear trends have emerged in the development of green shortest path optimization. When viewing the literature as a whole, there is an undeniable shift toward prioritizing environmental aspects, specifically carbon emissions.

The field is currently dominated by metaheuristic and evolutionary algorithms like NSGA-II and Genetic Algorithms. While these methods are powerful, they often struggle with high computational costs, making them difficult to apply in real time scenarios. This is a critical issue for transportation systems in developing countries, where traffic conditions are often unpredictable and diverse.

In contrast, deterministic approaches like the Lexicographic Method are often overlooked. This is a missed opportunity, as these methods provide clear benefits in terms of transparency. They allow for a strict prioritization of objectives ensuring, for instance, that emission reduction is prioritized over speed. The lack of research in this specific area highlights a clear gap in the literature.

Regarding implementation, there is still a divide between optimization models and actual GPS navigation data. Most studies use static data, ignoring the potential of real time GPS integration. This suggests that current models may not fully capture the reality of daily traffic.

Taken together, these findings suggest that future research needs to move beyond complexity for complexity's sake. Instead, the focus should be on creating models that are practical and effective in complex environments. The conceptual direction discussed in this study aims to answer this call for more applicable solutions.

5. Future Work

Based on the results of the bibliometric analysis, which demonstrate the dominance of topics related to Multi-Objective Optimization and carbon emissions alongside the limited application of hierarchical optimization methods in the context of developing countries, the primary agenda for future research is the development of a GPS-based eco-friendly path optimization model. This proposed framework is designed to directly address the gap identified in the literature, specifically the limited integration of dynamic optimization and emission analysis in green path models. By prioritizing carbon emission minimization through a strict lexicographic structure, the upcoming research aims to ensure that environmental sustainability is not merely an optional variable but the governing constraint of the optimization process. This approach is specifically tailored to address the unique challenges of developing countries, where traffic unpredictability often renders static models ineffective.

To ensure the proposed framework is systematic and reproducible, the research stages are organized linearly from data acquisition to model validation. The process begins with the extraction of real-time traffic parameters via Google Maps API, which are then converted into a weighted graph representation. Subsequently, the optimization engine applies the Binary Integer Programming (BIP) formulation to solve the multi-objective problem hierarchically. This structured workflow allows for a clear translation of theoretical mathematical models into executable Python computations.

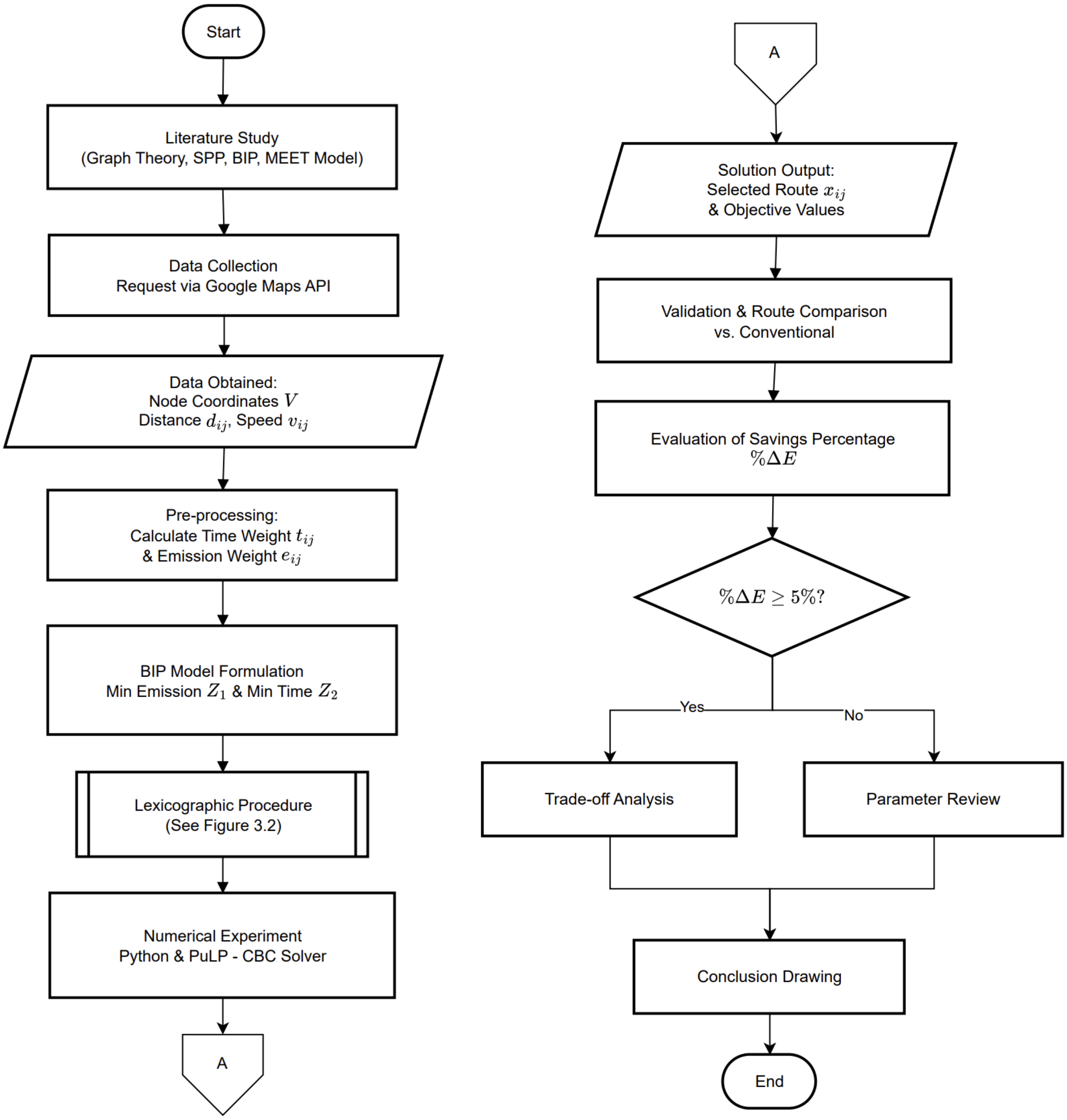
Crucially, the framework includes a validation phase, where a sensitivity analysis using a 5% emission reduction threshold serves as a decision gate. This benchmark is established to distinguish meaningful environmental benefits from stochastic traffic variations and GPS data noise, which are particularly high in heterogeneous traffic environments like Indonesia. By setting this minimum viability margin, the model ensures that the recommended green routes offer genuine savings beyond the margin of error, balancing sustainability with operational efficiency.

The proposed research design consists of the following interconnected stages:

1. **Literature Study Collection**
   A SLR will be conducted to identify the latest models in the shortest path problem, Multi-Objective Optimization, and carbon emission reduction methods. The literature review will cover studies on algorithm optimization, dynamic programming, and simulation-based approaches relevant to the context of green transportation.

2. **Collection of Path Distance and Speed Data from Google Maps**
   Historical data regarding path distance and vehicle speed will be collected using the Google Maps API. This data will be used to estimate model parameters such as travel time, fuel consumption, and carbon emissions generated on various alternative shortest paths.
3. **Graph Formation**
   The road network structure will be represented in the form of a graph, where nodes represent location points (origin, destination, and waypoints) while edges represent road segments with attributes of distance, time, and emission estimation. This graph formation will serve as the basis for the shortest path optimization process.
4. **Arc Weight Calculation**
   Each road segment (edge) in the graph will be assigned weights based on multiple criteria, including travel distance, travel time, and estimated carbon emissions. Weight calculation will consider factors such as average speed, road gradient, and traffic conditions to produce a realistic representation of the travel cost.
5. **BIP Model Formulation (Binary Integer Programming)**
   A Binary Integer Programming (BIP) model will be formulated to determine the optimal shortest path considering multiple objectives. Since the decision variables representing the selected path segments are binary ($x_{ij} \in \{0,1\}$), the formulation is specifically defined as a BIP model. The model will include objective functions for emission minimization and time minimization subject to network flow constraints.
6. **Lexicographic Method Formulation**
   The Lexicographic Method will be applied to solve the Multi-Objective Optimization problem by establishing a priority order. This approach will solve the objectives hierarchically, where the high priority objective (emission minimization) is solved first, and then the next objective (time minimization) is solved without degrading the quality of the previous objective's solution.
7. **Numerical Simulation with Python**
   Computational implementation will be carried out using Python with optimization libraries such as PuLP to solve the BIP model. Simulations will be run on various shortest path scenarios and vehicle parameters to evaluate the model's performance under various operational conditions.
8. **Model Validation and Sensitivity Analysis**
   The proposed model will undergo validation through trade-off analysis and parameter review, covering the evaluation of significant emission savings, variations in traffic patterns, and fluctuations in vehicle speed. Results will be visualized and analyzed to generate conclusions and practical implementation suggestions for transportation operators and policymakers in the green transportation sector.

To illustrate the comprehensive structure and sequence of this research methodology, the following flowcharts present the main steps of the study and the detailed lexicographic optimization procedure.



(a) Main Research Flowchart **(b)** Continuation of the Main Research Flowchart

Fig. 4: Overall Research Flowchart

The subsequent flowchart illustrates the procedure used to determine the optimal solution based on the Lexicographic Multi-Objective Optimization approach.

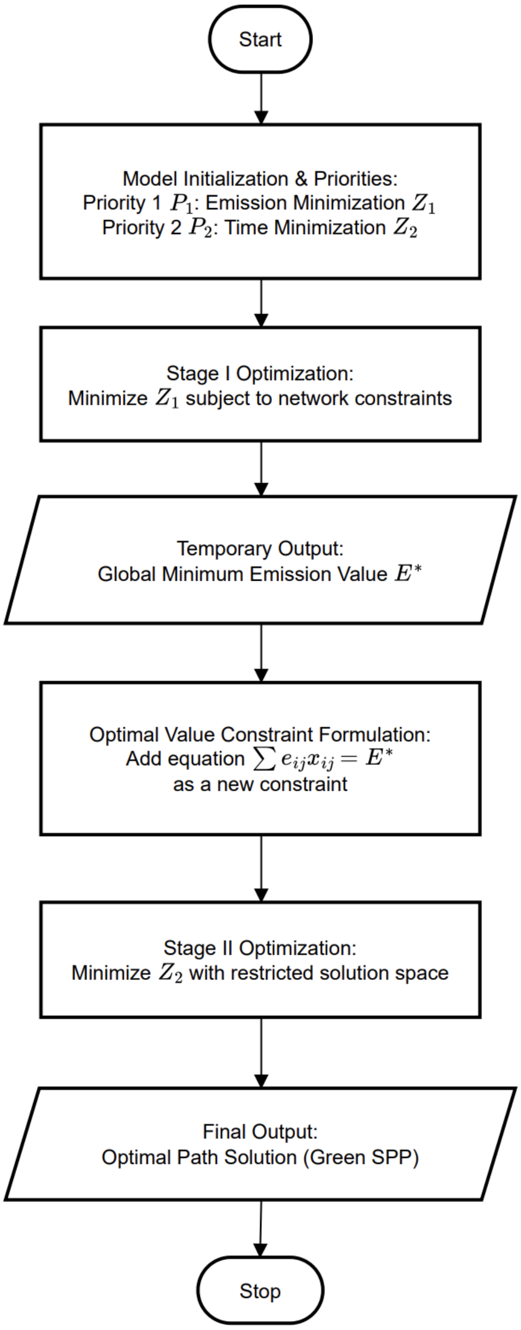


Fig. 5: Lexicographic Method Flowchart for Multi-Objective Optimization

6. Conclusion

This study has presented a Systematic Literature Review (SLR) and bibliometric analysis of 20 selected articles published between 2021 and 2025 regarding green shortest path optimization. The review reveals that the field is currently dominated by metaheuristic and AI-based methods (approximately 70% of studies), such as Genetic Algorithms and PSO. While effective, these methods often require high computational resources. In contrast, transparent, deterministic approaches like the Lexicographic method remain underutilized. Additionally, there is a lack of studies that effectively incorporate real-time GPS data within a multi-objective framework, especially in the context of developing countries.

Based on these findings, this paper contributes a conceptual framework for a GPS-based Lexicographic Multi-Objective Optimization model. The proposed model uniquely prioritizes carbon emission minimization as the primary objective, followed by travel time, offering a structured and transparent decision-making tool for sustainable urban transportation.

However, this study has several limitations that must be acknowledged. First, the literature search was restricted to three specific databases (Scopus, ScienceDirect, and Dimensions), which may have excluded relevant studies from other sources. Second, the final sample size of 20 articles is relatively small, reflecting the niche nature of this topic. Most importantly, the mathematical framework presented in this study is currently conceptual and has not yet been validated with large-scale empirical field data. Therefore, future research should focus on the full computational implementation of the proposed model using real-world traffic datasets (e.g., from Jakarta or Bandung) and conduct a comparative analysis against traditional shortest-path algorithms to quantify the trade-offs between solution quality and computational time.

CRediT Authorship Contribution Statement

Thania Nur Salsabila: Conceptualization, Methodology, Formal Analysis, Investigation, Writing-Original Draft Preparation, Visualization **Diah Chaerani:** Writing-Review & Editing, Supervision, Project Administration. **Herlina Napitupulu:** Supervision, Validation.

Declaration of Generative AI and AI-assisted technologies

The authors used ChatGPT (OpenAI) to assist in language refinement and structural clarity of the manuscript. All content generated with the assistance of this tool was critically reviewed, revised, and validity by authors. The authors take full responsibility for the originality, accuracy, and of the final manuscript.

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References

[1] Singiresu S. Rao. *Engineering Optimization: Theory and Practice*. 5th. Hoboken, NJ: John Wiley & Sons, 2020.

[2] H. Napitupulu, E. Carnia, N. Anggriani, and A. K. Supriatna. "Centrality measures in transportation networks for Unpad campus route". In: *Journal of Physics: Conference Series* 1722.1 (2021), p. 012063. DOI: 10.1088/1742-6596/1722/1/012063.

[3] John Current and Michael Marsh. "Multiobjective transportation network design and routing problems: Taxonomy and annotation". In: *European Journal of Operational Research* 65.1 (1993), pp. 4–19. DOI: 10.1016/0377-2217(93)90140-I.

[4] C. C. Azis, D. Chaerani, and E. Rusyaman. "Analysis of multi-objective linear robust optimization model with lexicographical method". In: *Media Statistika* 17.1 (2024), pp. 57–68. DOI: 10.14710/medstat.17.1.57-68.

[5] D. Chaerani, S. R. Adawiyah, and E. Lesmana. "Robust Optimization Model for Bi-objective Emergency Medical Service Design Problem with Demand Uncertainty". In: *Jurnal Teknik Industri* 20.2 (2018), pp. 95–104. DOI: 10.9744/jti.20.2.95-104.

[6] K. Thakur, S. Maity, P. Nielsen, T. Pal, and M. Maiti. "A 3D multiobjective multi-item eco-routing problem for refrigerated fresh products delivery using NSGA-II with hybrid chromosome". In: *Computers & Industrial Engineering* 198 (2024), p. 110644. DOI: 10.1016/j.cie.2024.110644.

[7] A. Mahmoodi, L. Hashemi, J. Laliberte, and S. M. Sajadi. "Optimizing energy and CO2 efficiency in last-mile delivery using hybrid fleet models". In: *Sustainable Futures* 10 (2025), p. 101089. DOI: 10.1016/j.sftr.2025.101089.

[8] H. Sun, M. He, Y. Gai, and J. Cao. "Optimization of Fresh Food Logistics Routes for Heterogeneous Fleets in Segmented Transshipment Mode". In: *Mathematics* 12.23 (2024), p. 3831. DOI: 10.3390/math12233831.

[9] A. Sabet and B. Farooq. "Exploring the combined effects of major fuel technologies, eco-routing, and eco-driving for sustainable traffic decarbonization in downtown Toronto". In: *Transportation Research Part A: Policy and Practice* 192 (2025), p. 104385. DOI: 10.1016/j.tra.2025.104385.

[10] S. M. Nasution, E. Husni, K. Kuspriyanto, and R. Yusuf. "Heterogeneous Traffic Condition Dataset Collection for Creating Road Capacity Value". In: *Big Data and Cognitive Computing* 7.1 (2023), p. 40. DOI: 10.3390/bdcc7010040.

[11] Institute for Essential Services Reform (IESR). *Wilayah Perkotaan di Pulau Jawa Menjadi Kontributor Tertinggi Emisi Karbon Individu*. 2025. https://iesr.or.id/wilayah-perkotaan-di-pulau-jawa-menjadi-kontributor-tertinggi-emisi-karbon-individu/.

[12] A. W. Deendarlianto, T. Widodo, I. Handika, I. C. Setiawan, and A. Lindasista. "Modelling of Indonesian road transport energy sector in order to fulfill the national energy and oil reduction targets". In: *Renewable Energy* 146.2 (2020), pp. 504–518. DOI: 10.1016/j.renene.2019.06.169.

[13] Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia. *Long-Term Strategy for Low Carbon and Climate Resilience 2050*. 2021. https://unfccc.int/sites/default/files/resource/Indonesia_LTS-LCCR_2021.pdf.

[14] B. Kitchenham and S. Charters. *Guidelines for Performing Systematic Literature Reviews in Software Engineering*. Technical Report EBSE 2007-001. Joint Report. Keele, UK: Keele University and Durham University, 2007.

[15] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman. "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement". In: *Annals of Internal Medicine* 151.4 (Aug. 2009). Epub 2009 Jul 20, pp. 264–269. DOI: 10.7326/0003-4819-151-4-200908180-00135.

[16] A. Pritchard. "Statistical bibliography or bibliometrics". In: *Journal of Documentation* 25.4 (1969), pp. 348–349.

[17] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim. "How to conduct a bibliometric analysis: An overview and guidelines". In: *Journal of Business Research* 133 (2021), pp. 285–296. DOI: 10.1016/j.jbusres.2021.04.070.

[18] N. J. Van Eck and L. Waltman. "Software survey: VOSviewer, a computer program for bibliometric mapping". In: *Scientometrics* 84.2 (2010), pp. 523–538. DOI: 10.1007/s11192-009-0146-3.

[19] Marsudi. *Teori Graf*. Malang: UB Press, 2016.

[20] A Hickman, D Hassel, R Joumard, Z Samaras, and S Sorenson. *Methodology for calculating transport emissions and energy consumption*. Project Report SE/491/98. Crowthorne, Berkshire, UK: Transport Research Laboratory (TRL), 1999.

[21] E. Demir, T. Bektas, and G. Laporte. "A Review of Recent Research on Green Road Freight Transportation". In: *European Journal of Operational Research* 229.3 (2013), pp. 775–793. DOI: 10.1016/j.ejor.2013.12.033.

[22] Alexander Schrijver. *Combinatorial Optimization*. Springer, 2017.

[23] I. Zupic and T. Ćater. "Bibliometric Methods in Management and Organization". In: *Organizational Research Methods* 18.3 (2015), pp. 429–472. DOI: 10.1177/1094428114562629.

[24] M. E. Falagas, E. I. Pitsouni, G. A. Malietzis, and G. Pappas. "Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and Weaknesses". In: *The FASEB Journal* 22.2 (2008), pp. 338–342. DOI: 10.1096/fj.07-9492LSF.

[25] V. Pradeep, R. Khemmar, and F. Jendoubi. "Visual Eco-Routing (VER): XGBoost Based Eco-Route Selection from Road Scenes and Vehicle Emissions". In: *IEEE Access* 12 (2024), pp. 9669–9681. DOI: 10.1109/ACCESS.2024.3353036.

[26] Adel Elgammal. "Integrated Path Planning and Speed Control for Electric Vehicles Using MOPSO-Based Optimization". In: *International Journal of Innovative Science and Research Technology* 10.5 (2025). DOI: 10.38124/ijisrt/25may1547.

[27] C. Zhu and X. Zhu. "Multi-Objective Path-Decision Model of Multimodal Transport Considering Uncertain Conditions and Carbon Emission Policies". In: *Symmetry* 14.2 (2022), p. 221. DOI: 10.3390/sym14020221.

[28] X. Yang and H. Jiang. "Research on Urban Cold Chain Logistics Path Optimization Considering Multi-Center and Time-Varying Road Networks". In: *IEEE Access* 12 (2024), pp. 71331–71348. DOI: 10.1109/ACCESS.2024.3402833.

[29] L. Li, H. Liang, J. Wang, J. Yang, and Y. Li. "Online Routing for Autonomous Vehicle Cruise Systems with Fuel Constraints". In: *Journal of Intelligent & Robotic Systems* 104.4 (2022), p. 68. DOI: 10.1007/s10846-021-01530-y.

[30] D. Saxena, N. Singh, K. Gupta, A. Verma, V. Mishra, J. Kumar, and A. K. Singh. "An Intelligent Multi-Depot Vehicle Routing and Management Model for Smart Cities". In: *IEEE Transactions on Intelligent Transportation Systems* 26.6 (2025), pp. 7740–7754. DOI: 10.1109/TITS.2025.3557826.

[31] L. Yang, C. Zhang, and X. Wu. "Multi-Objective Path Optimization of Highway-Railway Multimodal Transport Considering Carbon Emissions". In: *Applied Sciences* 13.8 (2023), p. 4731. DOI: 10.3390/app13084731.

[32] J. Wu, Q. Luo, and Y. Zhou. "Modified Dung Beetle Optimizer with Multi-Strategy for Uncertain Multi-Modal Transport Path Problem". In: *Journal of Computational Design and Engineering* 11.4 (2024), pp. 40–72. DOI: 10.1093/jcde/qwae058.

[33] F. Cheng and S. Jia. "Improved GA-LNS Algorithm for Solving Vehicle Path Problems Considering Carbon Emissions". In: *Applied Sciences* 14.21 (2024), p. 9956. DOI: 10.3390/app14219956.

[34] Y. Benmessaoud, L. Cherrat, and M. Ezziyyani. "Real-Time Self-Adaptive Traffic Management System for Optimal Vehicular Navigation in Modern Cities". In: *Computers* 12.4 (2023), p. 80. DOI: 10.3390/computers12040080.

[35] C. Qi. "Multi-Objective Optimization-Based Algorithm for Selecting the Optimal Path of Rural Multi-Temperature Zone Cold Chain Dynamic Logistics Intermodal Transportation". In: *International Journal of Computational Intelligence Systems* 17.1 (2024), p. 224. DOI: 10.1007/s44196-024-00616-3.

[36] Qian Linyi. "Research on path selection system based on green transportation". In: *E3S Web of Conferences*. Ed. by EILCD. Vol. 275. EDP Sciences, 2021, p. 02043. DOI: 10.1051/e3sconf/202127502043. https://doi.org/10.1051/e3sconf/202127502043.

[37] N. Yin. "Research on Green Logistics Distribution Path Based on Genetic Algorithm". In: *Procedia Computer Science* 261 (2025), pp. 1036–1042. DOI: 10.1016/j.procs.2025.04.682.

[38] C. Ren, L. Lu, J. Teng, C. Yin, J. Li, H. Ji, and F. Fu. "Logistics Distribution Path Optimization Considering Carbon Emissions and Multifuel-Type Vehicles". In: *Journal of Advanced Transportation* 2025 (2025), p. 6668589. DOI: 10.1155/ATR/6668589.

[39] Y. Zhang, G. Shi, and J. Liu. "Dynamic Energy-Efficient Path Planning of Unmanned Surface Vehicle Under Time-Varying Current and Wind". In: *Journal of Marine Science and Engineering* 10.6 (2022), p. 759. DOI: 10.3390/jmse10060759.

[40] X. Hu, K. Hu, D. Tao, Y. Zhong, and Y. Han. "GIS-Data-Driven Efficient and Safe Path Planning for Autonomous Ships in Maritime Transportation". In: *Electronics* 12.10 (2023), p. 2206. DOI: 10.3390/electronics12102206.

[41] X. Lu, J. Wang, C. W. Yuen, and Q. Liu. "Multi-Objective Intercity Carpooling Route Optimization Considering Carbon Emission". In: *Sustainability* 15.3 (2023), p. 2261. DOI: 10.3390/su15032261.

[42] A. A. Ibrahim, D. Leite, and C. De Bacco. "Sustainable Optimal Transport in Multilayer Networks". In: *Physical Review E* 105.6 (2022), p. 06432. DOI: 10.1103/PhysRevE.105.064302.

[43] W. Xu, Q. Liu, M. Chen, and H. Zeng. "Ride the Tide of Traffic Conditions: Opportunistic Driving Improves Energy Efficiency of Timely Truck Transportation". In: *IEEE Transactions on Intelligent Transportation Systems* 24.5 (2023), pp. 4777–4793. DOI: 10.1109/TITS.2023.3244757.

[44] Y. Kisialiou, A. Rialland, and V. Gribkovskaia. "Ship Model-Based Route Optimisation for Decision Support in Deep Sea Shipping". In: *Journal of Physics: Conference Series*. Vol. 2867. 1. IOP Publishing, 2024, p. 012012. DOI: 10.1088/1742-6596/2867/1/012012.