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Using DSM for Zoning of Tourism Flight Routes in Islands

Paniz Pourghadiri, Seyed Mohammadbagher Malaek

Sharif University of Technology, Iran, Tehran
Aerospace Department, IR

Abstract: This paper presents a DSM-based framework to optimize tourist flight zoning and routing between island clusters. Islands are modeled as nodes, with their interactions—based on proximity, infrastructure, and tourism potential—captured in a Design Structure Matrix (DSM). We use K-Means and Louvain clustering to define regions, apply Hall's Marriage Theorem for adaptive tourist-to-island assignment, and employ the Traveling Salesman Problem (TSP) to optimize intra-cluster flight paths. The methodology is validated using a dataset of 576 islands, and results are visualized with DSM diagrams, interaction graphs, and Mercator maps in MATLAB. This approach improves logistics efficiency and offers a scalable method for managing island tourism infrastructure. Rooted in systems engineering and graph theory, it enables modular planning and supports the development of sustainable flight networks, adaptable to other island geographies worldwide.

Keywords: Design Structure Matrix (DSM), Island Tourism, Tourism Flight Optimization, Clustering, TSP, Hall's Marriage Theorem

1 Introduction

Planning tourism infrastructure in island regions poses complex logistical and spatial challenges. The fragmented geography, variability in infrastructure quality, and fluctuating tourism demand render conventional planning methods less effective—particularly when applied uniformly across heterogeneous island clusters. These methods often fail to account for the systemic dependencies, spatial interconnectivity, and latent modularity inherent in such environments, leading to fragmented zones and inefficient routing.

From a systems engineering perspective, the Design Structure Matrix (DSM) offers a structured modeling tool to analyze interdependencies between components—in this case, islands—based on spatial, infrastructural, and touristic relationships. While DSM has been applied in product architecture and engineering domains, its application to spatial tourism planning remains largely unexplored.

This paper proposes a DSM-based, multi-layered methodology to address these challenges. Islands are modeled as interacting nodes, clustered using both K-Means and Louvain algorithms to define modular zones. Hall's Marriage Theorem is then applied to match tourists dynamically to islands, followed by routing optimization within clusters using the Traveling Salesman Problem (TSP). The approach is demonstrated on a dataset of 576 islands.

While the dataset is simulated, the goal is to construct a generalizable and scalable framework that can later be calibrated with empirical data. Tourists are not treated as a full domain in this iteration, but the structure is designed to accommodate tourist attributes in future work. The resulting model generates visual and quantitative outputs—DSM matrices, interaction graphs, and spatial maps—that support more coherent and sustainable tourism planning in island regions.

2 Related Work

The Design Structure Matrix (DSM) has long served as a powerful tool in systems engineering for representing and analyzing interdependencies among system components (Eppinger & Browning, 2012; Steward, 1981). Originally applied to organize product architectures and manage project workflows, DSM has since expanded into various fields such as transportation, infrastructure planning, and environmental system design (Lindemann et al., 2009; Maier et al., 2017). Its ability to formalize complex relationships in matrix form makes it a suitable approach for modeling the intricate interactions found in spatial planning tasks, including those involving tourism networks.

In tourism planning, zoning and clustering have traditionally relied on static metrics—such as geographic proximity or administrative boundaries—to group destinations (Pearce, 1995). While these methods provide initial structure, they often miss critical behavioral and infrastructural interrelations among destinations, such as seasonal flow patterns, intermodal transport connections, or the complementarity between different types of tourism (e.g., cultural vs. eco-tourism). These oversights can lead to fragmented and inefficient regional planning.

To address these limitations, recent research has turned toward network- and graph-based clustering methods. K-Means clustering has been widely used for spatial segmentation based on proximity and density (MacQueen, 1967; Lloyd, 1982), while Louvain modularity offers community detection in large, weighted networks through modularity maximization (Blondel et al., 2008). These algorithms provide more dynamic and behavior-aware clustering, capturing latent connections that are invisible to traditional zoning techniques. Their application in tourism has enabled more data-driven planning of regions and mobility flows (Baggio & Sainaghi, 2011; Zhao et al., 2020).

Route optimization is another key theme in tourism logistics. The Traveling Salesman Problem (TSP) has been extensively studied for optimizing itineraries in transportation and travel (Christofides, 1976; Laporte, 1992), yet it is rarely combined with adaptive allocation models. Hall's Marriage Theorem (Hall, 1935), rooted in graph theory, offers a principled method for many-to-many matching under constraints. While it has not seen widespread use in tourism contexts, its theoretical capacity to balance demand and supply makes it a compelling candidate for dynamic tourist assignment models—especially when spatial equity and fairness are important.

Despite progress in clustering and routing algorithms, most tourism planning models treat these components independently. This paper builds upon prior work by integrating clustering (K-Means, Louvain), adaptive assignment (Hall's Theorem), and routing (TSP) within a DSM-centric framework. By encoding island-level dependencies into the DSM, the proposed method allows for layered optimization across modules—facilitating planning that is not only efficient in distance terms, but also responsive to system complexity and sustainability goals. This unified structure offers a novel contribution to the intersection of spatial systems modeling and tourism infrastructure planning.

3 Methodology

This section presents a modular, multi-step methodology for the zoning and routing of tourism flight paths across island regions. The framework is built on the Design Structure Matrix (DSM), which serves as the central structure to encode spatial, infrastructural, and touristic relationships among islands (Eppinger & Browning, 2012). The method integrates data preprocessing, interaction modeling, clustering, assignment, route optimization, and visualization—each of which is described in detail below. The full pipeline was developed using MATLAB (Basemap), and supported by geospatial data platforms such as geojson.io and Oracle Spatial tools for spatial validation and processing.

3.1 Dataset Construction and Preprocessing

A custom dataset comprising 576 islands was developed by extracting and curating geospatial data from geojson.io. Islands were categorized according to oceanic divisions (e.g., Pacific, Indian Ocean) and further segmented by sub-oceanic seas (e.g., Andaman Sea, Banda Sea). Each island's record includes:

- Geographic coordinates (latitude, longitude)
- Land Area (in Km^2)
- Infrastructure attributes (e.g., airports, ferry ports)
- Tourism potential score, estimated based on indicators such as attraction type, density, accessibility, and regional presence

To ensure dataset reliability, preprocessing involved:

- Removal of duplicates and unusable entries
- Imputation of missing values or elimination of non-viable entries (e.g., Islands under 5 km)
- Standardization and normalization of numerical variables

Final validation and geospatial joins were performed using Oracle Spatial tools to ensure clean geometry and topological consistency. While the dataset is synthetic in nature, it is structured to accommodate future integration with empirical tourism data.

3.2 Design Structure Matrix (DSM) Construction

A DSM was constructed to represent pairwise interactions between islands, following techniques outlined in systems engineering and modularity design (Eppinger & Browning, 2012; Browning, 2001). Each matrix cell encodes the interaction strength between two islands, calculated from three weighted factors:

3.2.1 Geographical Proximity: Great-circle distance between island coordinates (shorter distance implies stronger interaction).

3.2.2 Tourism Potential Similarity: Euclidean distance of normalized tourism scores.

3.2.3 Infrastructure Connectivity: Binary and weighted assessment of transport links (e.g., direct air or sea route presence).

These dimensions were aggregated into a single interaction score using a weighted summation strategy, and the resulting DSM was symmetric and normalized. This matrix serves as the input structure for clustering and optimization.

3.3 Clustering via K-Means and Louvain Modularity

To segment islands into functional tourism zones, two clustering approaches were employed:

3.3.1 K-Means: A centroid-based clustering method applied on multidimensional features (coordinates, infrastructure index, tourism score). The optimal number of clusters (k) was selected using Elbow and Silhouette methods (MacQueen, 1967; Lloyd, 1982).

3.3.1 Louvain Modularity: A community detection algorithm from network science, applied directly to the DSM graph. It partitions nodes by maximizing intra-cluster edge density (Blondel et al., 2008).

Using both methods in tandem provides robustness: K-Means emphasizes spatial and attribute-based proximity, while Louvain captures latent connectivity structures within the DSM. This hybrid clustering ensures both geographic and functional coherence in the resulting zones (Zhao et al., 2020).

3.4 Tourist-to-Island Assignment Using Hall's Marriage Theorem

Once zones are defined, a graph-theoretic approach is used to assign tourists to islands within each cluster. Tourists are modeled with thematic preferences (e.g., eco-tourism, cultural, leisure), while islands have capacity constraints and thematic relevance scores.

Hall's Marriage Theorem is used to ensure a feasible and balanced allocation: each tourist node is matched to an eligible island such that no subset of tourists exceeds the total available capacity of its preferred destinations. This assignment method is dynamic and flexible, accommodating seasonal demand shifts and infrastructural limitations. While the model is demonstrated with simulated tourists, its structure is adaptable to real user data in future studies.

3.5 Routing Optimization with the Traveling Salesman Problem (TSP)

After tourists are assigned, intra-cluster routes are optimized using the Traveling Salesman Problem (TSP) to minimize total flight distance or time. Each zone is treated as a TSP instance, where the goal is to determine a minimal-cost cycle visiting each island exactly once.

Due to the NP-hard nature of TSP, heuristic solvers (e.g., 2-opt, nearest neighbor) were used to compute near-optimal solutions with low computational cost. The resulting flight routes improve operational efficiency while ensuring full network coverage.

This step addresses both logistical optimization and spatial equity by reducing the travel burden on both operators and tourists.

3.6 Visualization and Interpretation

Visualization plays a critical role in interpreting and communicating the results. Three main layers were used:

3.6.1 DSM Heatmaps: Show matrix structure and highlight interaction strength and modular zones.

3.6.2 Graph Visualizations: Display node connectivity, clusters, and centralities within the DSM network.

3.6.3 Mercator-Projected Maps: Created in MATLAB using geo-coordinates from geojson.io, these maps show real-world island positioning and optimized flight paths.

Geometric and topological validation of these outputs was conducted using Oracle spatial tools. These visual layers support stakeholder understanding, comparative analysis, and future policy-level deployment. The mapping framework also serves as a foundation for empirical calibration using actual tourism data in future phases of this research.

4 Results and Evolution

This section presents the outcomes of the proposed DSM-based methodology, including spatial mapping, clustering outputs, matrix visualizations, and adaptive tourist assignments. Each result illustrates how the integrated framework supports spatial coherence, logistical optimization, and balanced tourist distribution in island tourism systems.

4.1 Global Mapping of Islands (Mercator Projection)

As a preliminary step, all 576 islands were plotted using a Mercator projection based on their extracted latitude and longitude coordinates. This global visualization was created in MATLAB using geographic inputs obtained via geojson.io. Red dots represent each island across oceans and sub-oceanic zones.

This visual layer establishes a global spatial baseline and helps stakeholders understand geographic dispersion, accessibility challenges, and regional clustering potential. It sets the stage for interpreting the logic of subsequent clustering and routing phases.

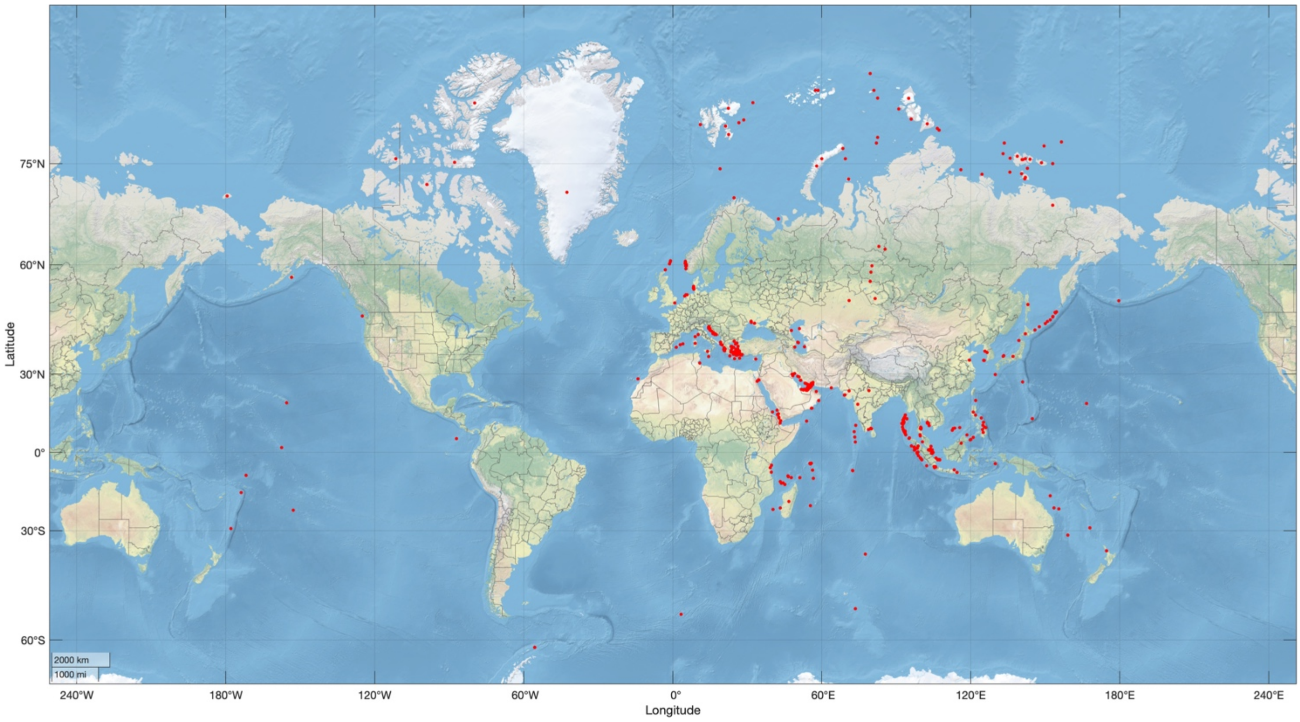

Figure 1. Geographic distribution of 575 islands on a Mercator world map.

4.2 Regional Clustering Output (Louvain-Based)

Islands were grouped into four primary clusters—East, North, South, and West—based on the Louvain modularity algorithm applied to the DSM interaction graph. Each region is color-coded on the map, enabling clear spatial differentiation of clusters.

These clusters reflect underlying geographic and infrastructural relationships, with islands sharing stronger internal connectivity grouped together. The segmentation promotes modular planning and supports the design of localized tourism strategies.

A clustered DSM was generated to visualize inter-island dependencies within and across regions. The matrix displays islands along both rows and columns, and each cell represents the normalized interaction score between a pair of islands. Color-coding highlights cluster membership based on Louvain output.

The diagonal blocks correspond to intra-cluster interactions, which appear denser and more structured—confirming the internal coherence of the defined regions. Sparse off-diagonal elements indicate limited cross-cluster dependencies, validating the modular decomposition.

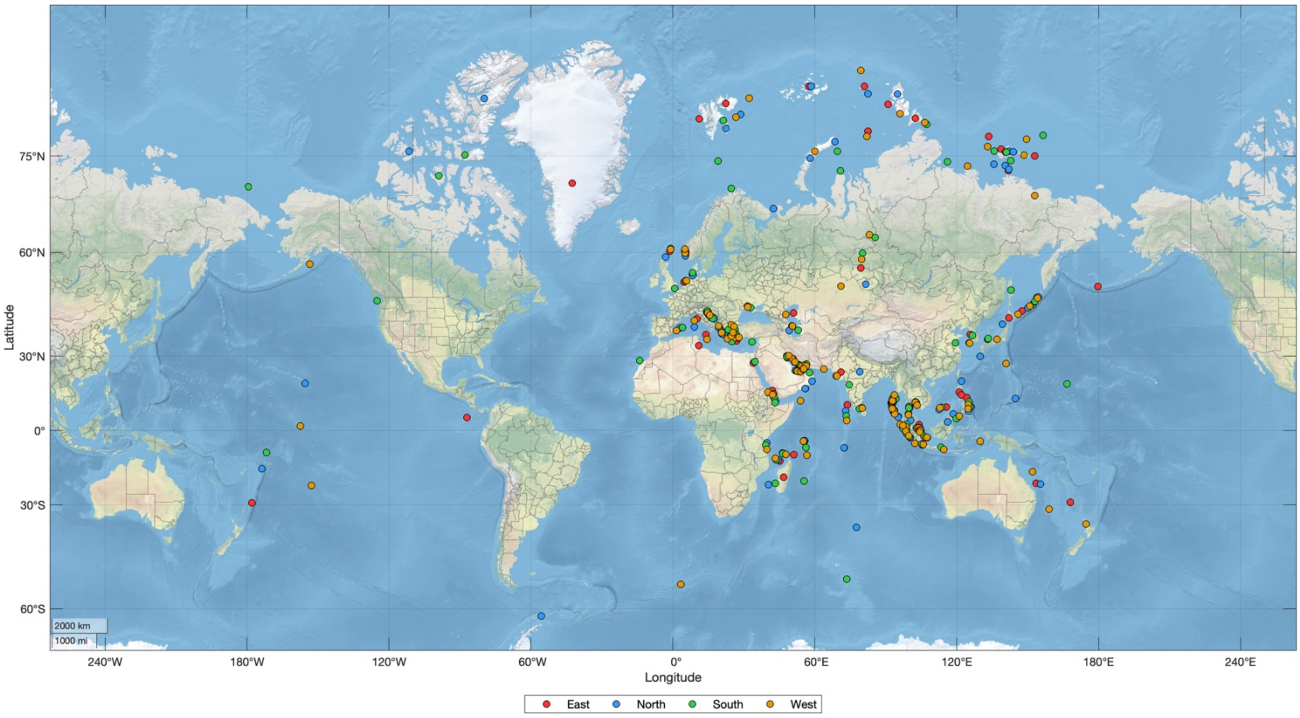

Figure 2. Louvain-based modular clustering of islands into four regional zones

4.3 Design Structure Matrix (DSM) with Cluster Coloring

A clustered DSM was generated to visualize inter-island dependencies within and across regions. The matrix displays islands along both rows and columns, and each cell represents the normalized interaction score between a pair of islands. And in general, it is divided into 5 zones with high accuracy using the K-Means method.

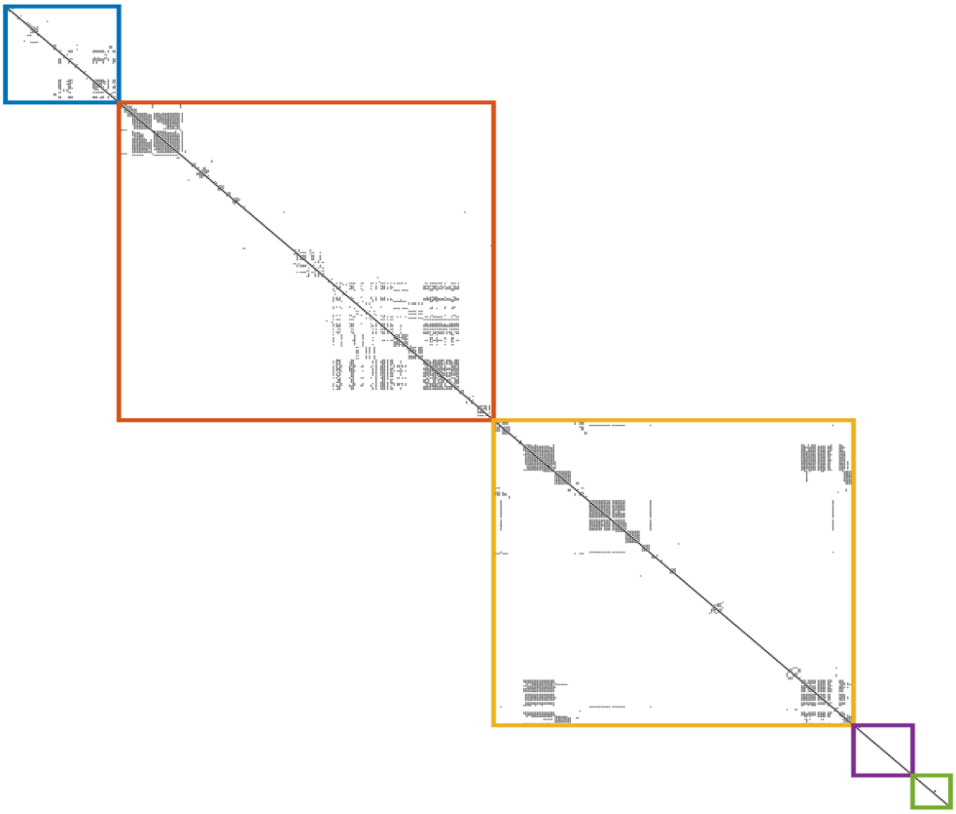

Figure 3. DSM sorted by K-Means clustering, showing modular island zones

4.4 Enhanced DSM Visualization for Interaction Interpretation

To aid visual interpretation, the DSM was reformatted:

- Matrix elements were enlarged to increase legibility
- The diagonal line was bolded to emphasize self-referential structure

This enhanced format makes it easier to identify high-interaction subgroups, potential outliers, or structurally isolated islands. The bold diagonal also helps emphasize the intra-zone cohesion that is critical for efficient tourism route planning.

4.5 Adaptive Tourist Assignment (Hall's Theorem)

To demonstrate equitable allocation of tourist demand, Hall's Marriage Theorem was applied within each cluster. Tourists (blue nodes) and islands (orange nodes) are represented in a bipartite graph; edges indicate feasible assignments that satisfy preference and capacity constraints.

The visual outcome shows a balanced and constraint-respecting matching, avoiding overcrowding while ensuring that all tourist profiles are accommodated. This method offers adaptability in fluctuating demand scenarios, providing a foundation for data-driven capacity management in real-world implementations.

Figure 4. Comparative visualization of tourist-to-island assignment under four Hall's model configurations

4.6 Summary of Framework Performance

Across all clusters, the integrated framework produced:

- Logically cohesive regional groupings
- Efficient intra-cluster routing with reduced travel overhead
- Balanced tourist distribution based on systemic feasibility

These outcomes validate the ability of the DSM-based approach to model complex spatial systems while incorporating both operational and behavioral constraints. While the results are based on a simulated dataset, the structure and logic of the framework are designed for transferability to empirical contexts.

5 Discussion

The results of this study confirm that combining DSM, clustering algorithms, adaptive matching, and routing optimization can offer a structured, scalable solution to the logistical complexity of island tourism planning. Beyond the individual performance of each component, the strength of this methodology lies in its integrated and modular design allowing for targeted analysis, scenario adaptation, and eventual real-world deployment.

5.1 Evaluating DSM-Based Clustering

The DSM framework enabled a clear representation of inter-island relationships by integrating spatial, infrastructural, and touristic dimensions into a unified matrix. This systemic view allowed for clustering that was not only based on geographic proximity, but also on functional connectivity—addressing a key shortcoming of conventional zoning techniques.

The Louvain algorithm further enhanced the clustering process by uncovering latent modular structures within the island network. These clusters showed strong internal cohesion and minimal cross-cluster interactions, validating the effectiveness of the DSM in supporting modular planning. Compared to static zoning approaches, this method offers a data-driven and dynamic mechanism to define tourism regions more accurately.

5.2 Adaptive Tourist Assignment: Practical Benefits

The use of Hall’s Marriage Theorem for tourist-to-island assignment represents a novel and practical innovation. While traditionally used in combinatorial optimization, applying it to tourism enables demand-responsive allocation based on preferences and capacity.

This ensures that no island is overloaded and that tourists are matched not just randomly or equally, but in a way that considers actual system constraints. The model is robust to seasonal changes, and can be adapted with empirical demand and supply profiles in future work. This step introduces fairness, load balancing, and flexibility into the core of tourism management.

5.3 Optimized Routing with TSP: Efficiency Gains

The application of the TSP within clusters yielded flight paths that significantly reduce intra-regional travel distance one of the main operational costs in island tourism. Although exact solutions to TSP are computationally infeasible at scale, heuristic approaches provided high-quality approximations in acceptable runtimes.

The implications extend beyond logistics: shorter routes reduce fuel use, emissions, and maintenance demands, thereby contributing to the environmental sustainability of island tourism—a growing concern for policymakers and operators alike.

5.4 Framework Scalability and Transferability

One of the framework’s core strengths is its modularity and adaptability. Although this study applied it to a dataset of 576 simulated islands, the structure is designed for transfer to real-world contexts. The DSM approach, by design, is agnostic to geography—it can be applied to any island cluster provided the necessary input data is available.

The combination of K-Means and Louvain allows flexibility between proximity-driven and network-driven clustering. Similarly, the tourist assignment model can integrate real tourist segmentation, and the routing module can be recalibrated for operator constraints (e.g., aircraft range, costs).

For planners, this means the method is not just academic—it provides a replicable planning toolkit that can support smarter tourism infrastructure investments, route scheduling, and capacity planning.

5.5 Limitations and Future Research

While the framework shows strong conceptual and computational performance, several limitations remain. First, the lack of empirical seasonal data limited the realism of tourist preferences and island capacities. Incorporating real-time or historical demand data would improve matching precision.

Second, while heuristic TSP solutions were adequate for this scale, larger systems or tighter constraints may require metaheuristic approaches such as simulated annealing or genetic algorithms. Future studies should explore these alternatives for greater efficiency.

Third, the model has not yet been tested in collaboration with real tourism agencies. A logical next step would be a pilot implementation in a defined island region (e.g., Andaman, Aegean, or Caribbean) to validate the practical viability of the approach.

Finally, the current model treats tourists as abstract demand nodes. In future iterations, tourists can be represented with demographic, behavioral, and preference-based profiles, transforming the model into a truly multi-domain planning tool that integrates user behavior into system optimization.

6 Conclusion

This study introduced an integrated methodology for planning and optimizing tourist flight routes across island systems using the Design Structure Matrix (DSM) as a central organizing framework. By combining DSM with clustering (K-Means, Louvain), adaptive matching (Hall's Marriage Theorem), and routing optimization (TSP), the proposed approach addresses both the structural and logistical complexities of managing tourism in archipelagic regions.

The results demonstrated that the method can successfully generate spatially coherent tourism zones, allocate tourists in a demand-responsive and capacity-aware manner, and reduce travel inefficiencies through optimized routing. Importantly, the modular structure of the framework supports reusability and scalability—making it adaptable to other island regions and tourism contexts worldwide.

Beyond computational performance, the methodology also contributes to sustainability and equity in tourism logistics by balancing resource use, minimizing environmental impact, and avoiding overcrowding at high-demand destinations.

Future work will focus on incorporating real-world data from tourism agencies, refining tourist preference models, and experimenting with advanced metaheuristic solvers to further improve the quality of routing solutions. The framework is also well-suited for integration with GIS systems and dynamic dashboards to support decision-makers in live planning environments.

Moreover, the ability to dynamically reconfigure clusters across seasons or geographic markets enables the design of flexible and diversified travel packages. This adaptability can help tourism operators expand market reach while keeping operational costs under control. In future extensions of this research, we also aim to explore its application in space tourism logistics, where cluster-based planning may contribute to economically viable scheduling and routing for travel to and from orbital hotels or space stations. The underlying principles of modularity, optimization, and system-level design remain equally relevant—even beyond Earth.

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Contact: P. Pourghadiri, Sharif University of Technology, Department of Aerospace Engineering, Azadi Street, P.O. Box 11155/1639, Tehran, Iran, Phone:+98 66160000, panizpourghadiri@gmail.com