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A BI-OBJECTIVE COST MINIMIZATION MODEL FOR THE INSULAR TOUR ROUTE PLANNING PROBLEM

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ABSTRACT

This article presents a study on the development of a bi-objective cost problem optimization model in planning tourist routes in the island zone. This problem is a new variant of the tour route plan problem. Bi-objective view of two cost components, namely maritime transportation costs and ground transportation costs. Two models were formulated using a mixed integer linear programming approach. The first model was designed to minimize one of the two cost components separately. The second model was bi-objective cost minimization based on the priority weights of the two costs. It was designed to determine minimum transportation costs based on priority weights. Model testing was carried out through numerical experiments on several cases that often occur in industries in Maluku, Indonesia, especially tourism and goods shipping. Each case has variations in the number of islands and nodes. As a result, the model can demonstrate its adaptability to changes in objectives and parameters. For cases that do not have a single solution, an increase in the network structure on the number of islands and nodes will increase the variety of efficient alternative solutions. The set of efficient solutions also shows an inverse relationship between MTC and GTC. The results also show that MTC minimization cannot be used as a reference for TC minimization in cases with many nodes and islands. Efforts to minimize MTC in the island zone impact reducing total costs but do not mean minimizing total costs. In addition, based on the exponential trend line of computing time, the number of nodes has a more significant influence on computing time compared to the number of islands.

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1. INTRODUCTION

The tour route plan problem (TRPP) is increasingly becoming a concern for operational research researchers today. Original TRPP was first used in the tourism sector to solve the problem of planning tourist tour routes to several points of interest [1]. TRPP is generally grouped into two types: single-tour TRPP and multi-tour TRPP [2]. The basic version of TRPP has correspondence with VRP [3]. The multi-tour TRPP can be considered an extension of the VRP, while the single-tour TRPP can be an extension of the TSP. This article introduces a new variant of TRPP and its cost bi-objective solution optimization model. This variant is found in the problem of determining tour routes or shipping goods in the island zone for single tours, which we will refer to hereafter as Insular TRPP (InTRPP).

The problem structure of this variant can be defined as follows. There are groups of islands (clusters) where each island has two sub-cluster points, namely: the POI (point of interest) sub-cluster and the CP (connection point) sub-cluster. The relationship between points is represented by an asymmetric travel cost matrix. The POI sub-cluster consists of one or several POIs that must be visited (i.e., tourist spots, survey locations, and hotels/inns), while the CP sub-cluster consists of one or several CPs that connect one island to another (i.e., harbors and airports). In contrast to POIs, not all CPs will be visited. Each CP will only be visited if it functions as a connecting route for arrivals or departures on an island. Routes are planned to start from and end at one of the POIs on the original island by ensuring that each POI and island must be visited exactly once with minimal transportation costs.

Those features make this issue unique from TSP and its variants. If islands are considered as clusters that restrict the nodes in them, and only one or a few nodes represent clusters to be visited, then this problem is similar to Generalized TSP (GTSP) [4]. However, if all nodes must be visited on each island, this problem is similar to Clustered TSP (CTSP) [5]. Various solutions for GTSP include integer programming formulation [6], [7], approximation algorithm [8]–[10], local search heuristics [11], [12], Lin–Kernighan–Helsgaun Algorithm [13], metaheuristics [14]. As for the CTSP, variations of the reported solutions include exact algorithms [15], approximation algorithms [16], local search heuristics [17], depth-first branch-and-bound search heuristics [18], and metaheuristics [19], [20]. However, both GTSP and CTSP assume that each cluster has no classification (partitioning) and special treatment of node collections.

Classification of a set of nodes in a cluster is discussed in the Clustered Generalized TSP (CGTSP) [21]. In CGTSP, a cluster can have smaller clusters or sub-clusters. However, the treatment of visits to each sub-cluster is the same, only represented by one node. In the InTRPP discussed this time, each island has two different treatment sub-clusters (POI and CP), at least one node in the POI sub-cluster and one in the CP sub-cluster. In addition, visits to the POI sub-cluster can be made once, while visits to the CP sub-cluster are made exactly twice when arriving and departing.

The classification and treatment of set nodes are discussed by Miranda et al. [22] and González et al. [23] in designing a waste collection system in the island zone of South Chile. This problem model was introduced as insular TSP, abbreviated InTSP [24]. In InTSP, each island's nodes are divided into two minor clusters: the port sub-cluster (including the depot) and the onshore waste service point sub-cluster. A visit to a port is influenced by the number of waste service points that will be served. Therefore, the decision to visit a port on an island may occur more than once. In addition, the ground transportation route from each service point is assumed to be direct and centralized (centroid) to the port without route consolidation. Other studies discussing ground transportation routing consolidation can be seen in the Hub Location Routing Problem (HLRP) [25]–[27]. When viewed from the route of the sea and landlines, InTSP has a ring-star structure, while HLRP has a ring-ring structure. HLRP is closer to the model structure discussed this time in this feature than InTSP. However, in HLRP, only one node in the CP sub-cluster functions as a hub.

Two visits to the CP sub-cluster on each island indicate that the VRP feature is also present. If it is assumed that there is only one CP in each CP sub-cluster, then this CP can act as a depot that forms two routes, routes to POIs and CPs on other islands. Because the number of CP sub-clusters is equal to the number of islands, it indicates that this case involves more than one depot. VRP with multiple depots is known as multi-depot VRP (MDVRP) [28]. There has been much discussion of MDVRP regarding alternative formulations [29], its integration with multi-period problems [30], and multi-trip [31]. The multi-depot problem is also discussed differently in the multi-depot routing problem (MDRP), which allows open routes to be carried out by vehicles by selecting an alternative depot as the endpoint [32]. Although

MDVRP and MDRP allow multiple depots to be involved in the network, the (global) route to link all depots needs to be discussed.

A similarly structured problem has been studied by Afifudin & Sahar [33]. This study designed a time minimization model using INLP for planning single-vehicle transportation routes in the Moluccas archipelago zone. The fundamental difference from the problems discussed in this article, lies in the design approach and the purpose of the model. The problem-solving model in this study was designed using mixed integer linear programming (MILP) with a bi-objective cost.

2. RESEARCH METHODS

This research takes the form of designing an optimization model that will be applied to solve the bi-objective problem of cost planning for a single trip route in the island zone. The system of model designed is adapted to real cases often faced by the tourism industry in Maluku, Indonesia. Mixed integer linear programming (MILP) is used to formulate the model. The models were programmed using Lingo software (version 18).

Two models were designed based on two situations. The first model was designed to determine minimum transportation costs separately, both maritime transportation costs (MTC) and ground transportation costs (GTC). This model also provides an objective function to minimize total costs (TC) to compare the results obtained from both (MTC and GTC). The main parameters in this model include the number of islands and nodes, the relationship between nodes and islands, and the costs between nodes. The primary decision variable is the route formed from the relationships between nodes, which are expressed in binary integers 0 or 1. The second model was designed to determine minimum transportation costs based on the priority weights (α) of MTC and GTC. The technique for designing this model is the same as the one used by Miranda et al. [24]. The parameters that need to be added include the ideal point for each cost (MTC_{min} and GTC_{min}), the anti-ideal point (MTC_{max}, GTC_{max}), and the cost priority weight α. The ideal and anti-ideal points of MTC and GTC are obtained from the results of the first model. The α value used ranges from 0 to 1. An α value close to zero indicates that the minimization objective is prioritized in GTC. On the other hand, if α is close to one, it means that the minimization objective is prioritized in MTC.

Model testing was done through numerical experiments of two models on a collection of cases. The aim is to see the level of adaptability and computational time capability. The model's adaptability level will be seen in the appropriateness of the value recommended by the model in one of the cases and the variation of the recommendations for the variation of the case. Meanwhile, the computational time capability of the model will be seen in the average model computation time for each case. The test is carried out using a computer with Intel® Celeron® CPU N3350 @ 1.10 GHz processor specifications and 2.00 GB RAM. This computer specification is used to determine the computing time of the model application when run on a computer with minimum specifications.

Each case has variations in the number of islands and nodes, both points of interest (POI) and connecting points between islands (CP). **Table 1** describes the set of cases used in the numerical experiments. Of the 17 cases, the first 13 cases are real cases, while the other 4 are fictional cases designed to discover the phenomenon of weight changes and determine computing time. The cases are arranged based on the ten planned islands, as in **Table 2**. **Table 3** shows the involvement of the islands in each case. In each experiment, island 1 is the origin island, and node one on Island 1 is the depot.

Data regarding the relationship between nodes and islands and transportation costs between nodes for each case can be accessed at https://data.mendeley.com/datasets/y7zhkfy7cm/3. Because it is assumed that each node is connected, to overcome the costs between two nodes that are not connected, both are given a large enough value. The same technique is also used to anticipate the formation of routes at the same two nodes.

Table 1. Rill Cases in Numerical Experiments

Case	# of islands	# of nodes		Sum. of nodes
		Point of interest (POI)	Connection point (CP)	
3-1	3	16	8	24
3-2	3	15	7	22
3-3	3	14	7	21
4-1	4	21	10	31
4-2	4	20	9	29
4-3	4	17	9	26
4-4	4	19	8	27
Case	# of islands	# of nodes		Sum. of nodes
		Point of interest (POI)	Connection point (CP)	
4-5	4	18	8	26
4-6	4	16	8	24
4-7	4	15	8	23
5-1	5	25	11	36
5-2	5	22	11	33
6-1	6	26	12	38
7-1	7	27	16	43
8-1	8	29	18	47
9-1	9	33	19	52
10-1	10	34	20	54

Table 2. Islands and Its Attributes

Island	# of nodes		Descript.	Connected islands
	Point of interest (POI)	Connection point (CP)		
1	3	2	rill	2, 3, 4, 7, 8, 9, and 10
2	7	3	rill	1, 3, 4, 5, 6, 7, 8, 9, and 10
3	6	3	rill	1, 2, 4, 5, 6, 7, 8, 9, and 10
4	5	2	rill	1, 2, 3, 5, 6, 7, 8, 9, and 10
5	4	1	rill	2, 3, 4, 7, 8, 9, and 10
6	1	1	rill	2, 3, 4, 7, 8, 9, and 10
7	2	2	fiction	1, 2, 3, 4, 5, 6, 8, 9, and 10
8	2	2	fiction	1, 2, 3, 4, 5, 6, 7, 9, and 10
9	2	2	fiction	1, 2, 3, 4, 5, 6, 7, 8, and 10
10	2	2	fiction	1, 2, 3, 4, 5, 6, 7, 8, and 9

Table 3. Island Engagement Plans for each Case

Case	Islands									
	1	2	3	4	5	6	7	8	9	10
3-1	√	√	√	-	-	-	-	-	-	-
3-2	√	√	-	√	-	-	-	-	-	-
3-3	√	-	√	√	-	-	-	-	-	-
4-1	√	√	√	√	-	-	-	-	-	-
4-2	√	√	√	-	√	-	-	-	-	-
4-3	√	√	√	-	-	√	-	-	-	-
4-4	√	√	-	√	√	-	-	-	-	-
4-5	√	-	√	√	√	-	-	-	-	-
4-6	√	√	-	√	-	√	-	-	-	-
4-7	√	-	√	√	-	√	-	-	-	-
5-1	√	√	√	√	√	-	-	-	-	-
5-2	√	√	√	√	-	√	-	-	-	-
6-1	√	√	√	√	√	√	-	-	-	-
7-1	√	√	√	√	-	-	√	√	√	-
8-1	√	√	√	√	-	-	√	√	√	√
9-1	√	√	√	√	√	-	√	√	√	√
10-1	√	√	√	√	√	√	√	√	√	√

3. RESULTS AND DISCUSSION

3.1 Model Development

3.1.1 Sets, indexes, parameters and decision variables

Sets and indexes:

- Q^1 = Set of islands, = {1, 2, …, L}
- Q^2 = Set of nodes, including POI and CP, {1, 2, …, M, M+1, M+2, …, N}. Node 1 is the depot.
- L = Number of islands
- M = Number of nodes excluding CPs
- N = Number of nodes
- a,b = Index for each island
- h,i,j = Index for each node

Parameters:

- z_{ai} = The binary variable indicates if point i is located on island a
- c_{ij} = Transportation cost from point i to point j
- C = Large value for costs indicates travel between two points cannot be carried out.

Decision variables:

- x_{ij} = The binary variable indicates if the trip from point i to point j is selected
- v_i = integer variable indicating the order of visits to point i, for land travel routes
- w_a = integer variable indicating the order of visits to island a, for sea travel routes.

3.1.2 Model I Formulation

Model I is a bi-objective optimization model without priority weights. Based on the previous notation, the problem is formulated in the mixed-integer linear programming (MILP) model as follows:

$$Min \left\{ \underbrace{\sum_{a\in Q^1}\sum_{b\in Q^1}\sum_{i\in Q^2}\sum_{j\in Q^2} x_{ij} z_{ai} z_{bj} c_{ij}}_{MTC} ; \underbrace{\sum_{a\in Q^1}\sum_{i\in Q^2}\sum_{j\in Q^2} x_{ij} z_{ai} z_{aj} c_{ij}}_{GTC} \right\} \quad (1)$$

$$Min \underbrace{\sum_{i\in Q^2}\sum_{j\in Q^2} x_{ij} c_{ij}}_{TC} \quad (2)$$

The objective of minimizing transportation costs partially (MTC and GTC) can be seen in **Equation (1)**, while the objective of minimizing total costs is in **Equation (2)**. Each goal is subject to the following constraints:

$$\sum_{h\in Q^2} x_{hi} = \sum_{j\in Q^2} x_{ij} \qquad ;\forall i \in Q^2 \quad (3)$$

$$\left.\begin{aligned} &\sum_{\substack{b\in Q^1\\ b\neq a}}\sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j>M\\ j\neq i}} x_{ij} z_{ai} z_{bj} = 1 \\ &\sum_{\substack{b\in Q^1\\ b\neq a}}\sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j>M\\ j\neq i}} x_{ij} z_{bi} z_{aj} = 1 \end{aligned}\right\} \quad ;\forall a \in Q^1 \quad (4)$$

$$\left.\begin{aligned} &\sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j\le M}} x_{ij} z_{ai} z_{aj} = 1 \\ &\sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j\le M}} x_{ji} z_{aj} z_{ai} = 1 \end{aligned}\right\} \quad ;\forall a \in Q^1 \quad (5)$$

$$\sum_{\substack{i\in Q^2\\ i\le M}}\sum_{\substack{j\in Q^2\\ j\le M}} x_{ij} z_{ai} z_{aj} = \left(\sum_{\substack{h\in Q^2\\ h\le M}} z_{ah}\right) - 1 \qquad ;\forall a\in Q^1 \tag{6}$$

$$\sum_{i\in Q^2}\sum_{j\in Q^2} x_{ij} z_{ai} z_{aj} = \left(\sum_{\substack{h\in Q^2\\ h\le M}} z_{ah}\right) + 1 \qquad ;\forall a\in Q^1 \tag{7}$$

$$\sum_{\substack{j\in Q^2\\ j>M}} x_{ij} z_{ai} z_{aj} = 0 \qquad ;\forall e\in Q^1, \forall i\in Q^2, i>M \tag{8}$$

$$\left(\sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j>M\\ j\ne i}} x_{ij} z_{ai} z_{bj} + \sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j>M\\ j\ne i}} x_{ij} z_{bi} z_{aj}\right) \le 1 \qquad ;\forall a,b\in Q^1, a\ne b \tag{9}$$

$$w_b - w_a \ge 1 - (L+1)\left(1 - \sum_{\substack{i\in Q^2\\ i>M}}\sum_{\substack{j\in Q^2\\ j>M\\ j\ne i}} x_{ij} z_{ai} z_{bj}\right) \qquad ;\forall a,b\in Q^1, b\ne 1 \tag{10}$$

$$\left.\begin{aligned} \sum_{\substack{b\in Q^2\\ b\ne a}}\sum_{\substack{h\in Q^2\\ h>M}} x_{hi} z_{bh} z_{ai} &= \sum_{\substack{j\in Q^2\\ j\le M}} x_{ij} z_{ai} z_{aj} \\ \sum_{\substack{h\in Q^2\\ h\le M}} x_{hi} z_{ah} z_{ai} &= \sum_{\substack{b\in Q^2\\ b\ne a}}\sum_{\substack{j\in Q^2\\ j>M}} x_{ij} z_{ai} z_{bj} \end{aligned}\right\} \qquad ;\forall a\in Q^1, \forall i\in Q^2, i>M \tag{11}$$

$$\left.\begin{aligned} \left(\sum_{\substack{j\in Q^2\\ j\le M\\ j\ne i}} x_{ij} z_{aj} + \sum_{\substack{h\in Q^2\\ h>M}} x_{ih} z_{ah}\right) z_{ai} &\le 1 \\ \left(\sum_{\substack{j\in Q^2\\ j\le M\\ j\ne i}} x_{ji} z_{aj} + \sum_{\substack{h\in Q^2\\ h>M}} x_{hi} z_{ah}\right) z_{ai} &\le 1 \end{aligned}\right\} \qquad ;\forall a\in Q^1, \forall i\in Q^3, i\le M \tag{12}$$

$$\left(\sum_{\substack{h\in Q^2\\ h>M}} x_{hi} z_{ah} + \sum_{\substack{j\in Q^2\\ j>M}} x_{ij} z_{aj}\right) z_{ai} \le 2 - \begin{cases} 1, & \sum_{\substack{i\in Q^2\\ i\le M}} z_{ai} > 1 \\ 0, & \sum_{\substack{i\in Q^2\\ i\le M}} z_{ai} = 1 \end{cases} \qquad ;\forall a\in Q^1, \forall i\in Q^2, i\le M \tag{13}$$

$$v_j z_{aj} - v_i z_{ai} \ge 1 - \left(\sum_{\substack{h\in Q^2\\ h\le M}} z_{ah} + 1\right)\left(1 - x_{ij} z_{ai} z_{aj}\right) \qquad ;a\in Q^1, \forall i,j\in Q^2, i>M, j\le M, i\ne j \tag{14}$$

$$v_j z_{aj} - v_i z_{ai} \ge 1 - \left(\sum_{\substack{h\in Q^2\\ h\le M}} z_{ah} + 1\right)\left(1 - x_{ij} z_{ai} z_{aj}\right) \qquad ;\forall a\in Q^1, \forall i,j\in Q^2, i\le M, j\le M, i\ne j \tag{15}$$

$$v_i z_{ai} \leq \sum_{\substack{h \in Q^2 \\ h \leq M}} z_{ah} \qquad ; \forall a \in Q^1, \forall i \in Q^2, i \leq M \tag{16}$$

$$x_{ij} = \{0,1\} \qquad ; \forall i, j \in Q^2 \tag{17}$$

$$x_{ij} \leq \begin{cases} 1, & c_{ij} < C \\ 0, & otherwise \end{cases} \qquad ; \forall i, j \in Q^2 \tag{18}$$

$$v_i \geq 0 \qquad ; \forall i \in Q^2 \tag{19}$$

$$v_i = INT \quad ; \quad v_i \geq 1 \qquad ; \forall i \in Q^2, i \leq M \tag{20}$$

$$w_a = INT \qquad ; \forall a \in Q^1 \tag{21}$$

$$w_a = 0 \qquad ; \forall a \in Q^1, a = 1 \tag{22}$$

Equation (3) generally regulates the alignment of entry and exit routes. In particular, **Equation (4)** ensures the arrival route to an island and each departure only once. **Equation (5)** to **Equation (7)** set the number of routes on each island. **Equation (8)** to **Equation (10)** ensure the elimination of subtour on sea routes. **Equation (11)** ensures the connection between sea and land routes on each island. Subtour elimination on the overland route was confirmed by **Equation (12)** to **Equation (16)**. The values and limits of the decision variables (x, v, and w) are set at **Equation (17)** to **Equation (22)**.

3.1.3 Model II Formulation

Model II is designed to optimize cost bi-objectives based on priority weights. The parameters that need to be added include the ideal point for each cost (MTC_{min} and GTC_{min}), the anti-ideal point (MTC_{max}, GTC_{max}), and the cost priority weight α. The ideal and anti-ideal points of MTC and GTC are obtained from the results of model I.

If Y represents the optimal solution for each α, then the bi-objective cost model based on priority weights can be formulated as **Equation (23)**. This bi-objective is subject to constraints on **Equation (3)** to **Equation (22)**.

$$Min \left(\alpha . \left(\frac{MTC(Y) - MTC_{min}}{MTC_{max} - MTC_{min}} \right) + (1-\alpha) \left(\frac{GTC(Y) - GTC_{min}}{GTC_{max} - GTC_{min}} \right) \right). \tag{23}$$

3.2 Numerical Experiment

3.2.1 Experiment with Model I on Real Cases

The first model was applied to 13 real cases, ranging from case 3-1 to case 6-1. A cost comparison can be seen in **Table 4** based on **Equation (1)** and **Equation (2)**, while route recommendations can be seen in **Table 5**. In general, there are similar results when minimizing maritime transportation cost (MTC) and total transportation cost (TC) in each case.

Table 4. Comparison of Costs Between Scenarios

Case	Minimize MTC			Minimize GTC			Minimize TC		
	MTC ($)	GTC ($)	TC ($)	MTC ($)	GTC ($)	TC ($)	MTC ($)	GTC ($)	TC ($)
3-1	25.3	13.5	38.8	31.3	12.7	44	25.3	13.5	38.8
3-2	29	13.4	42.4	30	13.2	43.2	29	13.4	42.4
3-3	25.7	13.5	39.1	43.7	13	56.7	25.7	13.7	39.4
4-1	30.7	19.3	50	46.7	18.7	65.4	30.7	19.3	50
4-2	27.5	17.4	44.9	27.5	17.4	44.9	27.5	17.4	44.9
4-3	28.1	13.2	41.3	28.1	13.2	41.3	28.1	13.2	41.3
4-4	40	18.1	58.1	40.5	17.9	58.5	40	18.1	58.1
4-5	47.7	17.7	65.4	47.7	17.7	65.4	47.7	17.7	65.4
4-6	44.3	13.9	58.2	46.6	13.7	60.3	44.3	13.9	58.2
4-7	48.6	13.5	62.1	48.6	13.5	62.1	48.6	13.5	62.1
5-1	37	24.3	61.3	42.9	23.5	66.3	37	24.3	61.3
5-2	37.6	20	57.7	43.4	19.2	62.7	37.6	20	57.7
6-1	54.4	24	78.4	54.4	24	78.4	54.4	24	78.4

Table 5. Different Routes of the Scenarios

Case	Minimize	Route
3-1	MTC or TC	1-2-18-20-10-6-7-9-4-8-5-20-23-16-11-12-13-14-15-23-18-3-1
	GTC	1-2-18-23-15-14-11-16-13-12-24-21-10-6-7-9-4-8-5-20-18-3-1
3-2	MTC or TC	1-2-17-19-10-6-8-5-7-9-4-20-22-12-13-14-15-11-21-17-3-1
	GTC	1-2-17-21-11-14-15-13-12-22-20-10-6-7-9-4-8-5-19-17-3-1
3-3	MTC or TC	1-2-16-18-9-4-5-6-7-8-18-20-14-13-12-11-10-20-16-3-1
	GTC	1-2-16-18-8-7-4-9-6-5-19-21-11-12-13-14-10-20-16-3-1
4-1	MTC or TC	1-2-23-28-16-11-12-13-14-15-28-30-17-20-21-19-18-31-26-10-6-7-9-4-8-5-25-23-3-1
	GTC	1-2-23-28-15-14-11-16-13-12-29-26-10-6-8-5-7-9-4-26-31-18-19-20-21-17-30-23-3-1
4-2	MTC, GTC, or TC	1-2-22-27-15-14-11-16-13-12-28-29-20-18-17-19-29-25-10-6-7-9-4-8-5-24-22-3-1
4-3	MTC, GTC, or TC	1-2-19-24-15-14-11-16-13-12-25-26-17-26-22-10-6-7-9-4-8-5-21-19-3-1
4-4	MTC or TC	1-2-21-23-10-6-8-5-7-9-4-24-27-19-17-16-18-27-26-12-13-14-15-11-25-21-3-1
	GTC	1-2-21-25-11-14-15-13-12-26-27-19-17-16-18-27-24-10-6-7-9-4-8-5-23-21-3-1
4-5	MTC, GTC, or TC	1-2-20-22-8-7-4-9-6-5-23-26-18-16-15-17-26-25-11-12-13-14-10-24-20-3-1
4-6	MTC or TC	1-2-18-20-10-6-8-5-7-9-4-21-24-16-24-23-12-13-14-15-11-22-18-3-1
	GTC	1-2-18-22-11-14-15-13-12-23-24-16-24-21-10-6-7-9-4-8-5-20-18-3-1
4-7	MTC, GTC, or TC	1-2-17-19-8-7-4-9-6-5-20-23-15-23-22-11-12-13-14-10-21-17-3-1
5-1	MTC or TC	1-2-27-29-10-6-8-5-7-9-4-30-36-25-23-22-24-36-33-12-11-16-13-14-15-32-34-18-19-20-21-17-34-27-3-1
	GTC	1-2-27-32-15-14-11-16-13-12-33-36-25-23-22-24-36-30-10-6-8-5-7-9-4-30-35-18-19-20-21-17-34-27-3-1
5-2	MTC or TC	1-2-24-26-10-6-8-5-7-9-4-27-33-22-33-30-12-11-16-13-14-15-29-31-18-19-20-21-17-31-24-3-1
	GTC	1-2-24-29-15-14-11-16-13-12-30-27-10-6-8-5-7-9-4-27-33-22-33-32-18-19-20-21-17-31-24-3-1
6-1	MTC, GTC, or TC	1-2-28-33-15-14-11-16-13-12-34-38-26-38-31-10-6-8-5-7-9-4-31-37-25-23-22-24-37-36-18-19-20-21-17-35-28-3-1

Striking similarities are seen in cases 6-1, 4-2, 4-3, 4-5, and 4-7, where the models recommend the same solution in each scenario. That is, to get the minimum total transportation costs (TC), maritime transportation costs (MTC), or ground transportation costs (GTC), the recommended route stays the same. Generally, this phenomenon occurs when only one optimal solution (single solution) can be recommended. For example, in case 6-1, to get the minimum TC, MTC, or GTC, the recommended island order is 1-3-6-2-5-4-1, while the sequence of nodes is 1-2-28-33-15-14-11-16-13-12-34-38-26-38-31-10-6-8-5-7-9-4-31-37-25-23-22-24-37-36-18-19-20-21-17-35-28-3-1 (see **Figure. 1**). With this route, the MTC issued is $54.4, and the GTC is $24.

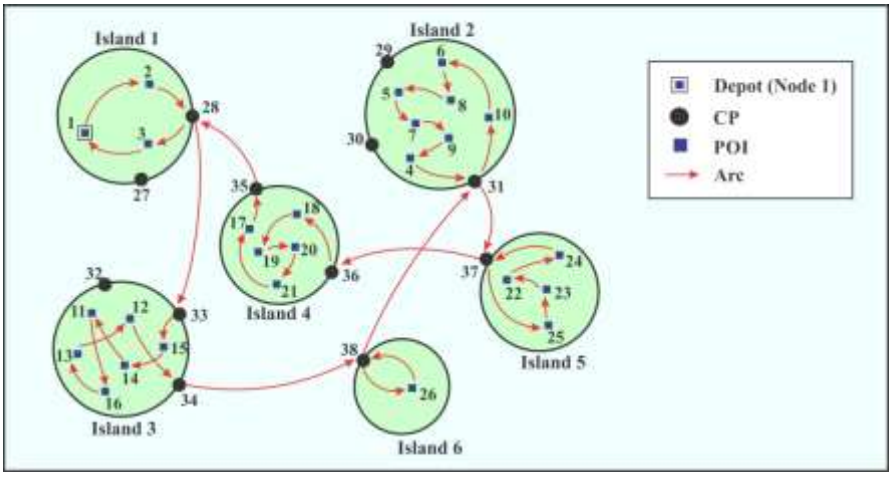
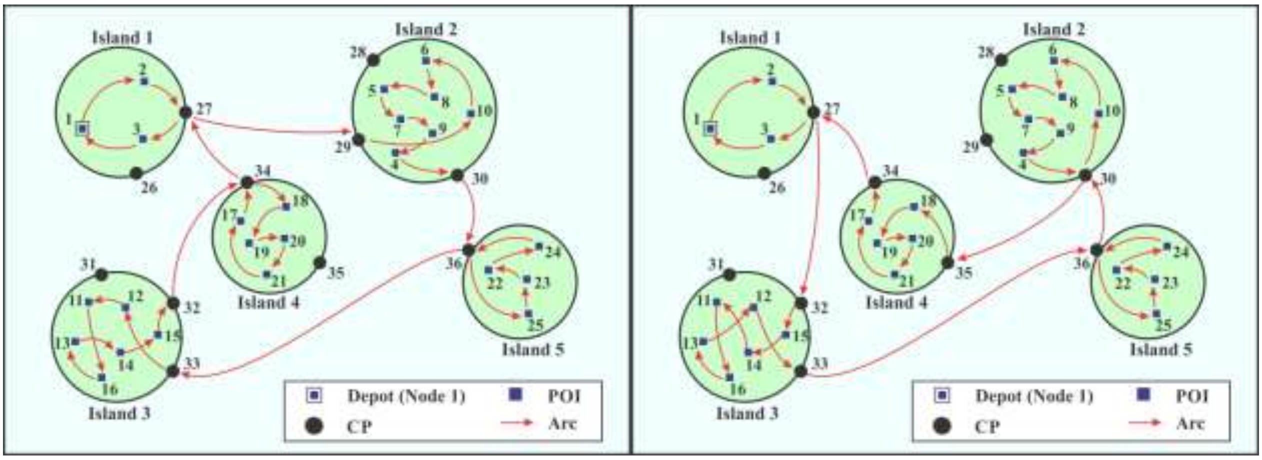


Figure 1. Optimal Result In Case 6-1

The different results can be seen in seven cases: 3-1, 3-2, 3-3, 4-1, 4-4, 4-6, 5-1, and 5-2. In these cases, the model provides different solutions between minimizing MTC or TC versus minimizing GTC. For example, in case 5-1(see **Figure. 2**), when minimizing MTC, the recommended island visiting route in sequence is 1-2-5-3-4-1. The same route recommendation is given when minimizing TC. However, when GTC is minimized, the island visit route changes to 1-3-5-2-4-1. As a result of minimizing GTC, TC increased by 8.2% compared to MTC. These results show that maritime transportation has a significant effect on TC, as well as proving that the model adapts to changes in a given scenario.



(a) (b)

Figure 2. Optimal Result In Case 5-1: (a) minimize MTC or TC, (b) minimize GTC

3.2.2 Experiment with Model II on All Cases

The following experiment is to apply model II to each case by adjusting the cost priority weight α based on Equation (23). This experiment was conducted to study the relationship between MTC and GTC further. A summary of the results can be seen in Table 6.

Table 6. Efficient Solution Sets for 12 Cases That Are Not A Single Solution

Case	α	MTC ($)	GTC ($)	TC ($)	Route
3-1	0.0 - 0.5	31.33	12.66	43.99	1-2-18-23-15-14-11-16-13-12-24-21-10-6-7-9-4-8-5-20-18-3-1
	0.6 - 1	25.33	13.46	38.79	1-2-18-20-10-6-7-9-4-8-5-20-23-16-11-12-13-14-15-23-18-3-1
3-2	0.0 - 0.5	30	13.20	43.2	1-2-17-21-11-14-15-13-12-22-20-10-6-7-9-4-8-5-19-17-3-1
	0.6 - 1	29.00	13.39	42.39	1-2-17-19-10-6-8-5-7-9-4-20-22-12-13-14-15-11-21-17-3-1
3-3	0.0 - 0.4	43.66	13.00	56.66	1-2-16-18-8-7-4-9-6-5-19-21-11-12-13-14-10-20-16-3-1
	0.5 - 1	25.66	13.72	39.39	1-2-16-18-9-4-5-6-7-8-18-20-14-13-12-11-10-20-16-3-1
4-1	0.0 - 0.4	46.66	18.71	65.37	1-2-23-28-15-14-11-16-13-12-29-26-10-6-8-5-7-9-4-26-31-18-19-20-21-17-30-23-3-1
	0.5 - 1	30.66	19.32	49.99	1-2-23-28-16-11-12-13-14-15-28-30-17-20-21-19-18-31-26-10-6-7-9-4-8-5-25-23-3-1
4-2	0.0 - 1	17.4	17.4	34.8	1-2-22-27-15-14-11-16-13-12-28-29-20-18-17-19-29-25-10-6-7-9-4-8-5-24-22-3-1
4-3	0.0 - 1	13.2	13.2	26.4	1-2-19-24-15-14-11-16-13-12-25-26-17-26-22-10-6-7-9-4-8-5-21-19-3-1
4-4	0.0 - 0.4	40.54	17.94	58.48	1-2-21-25-11-14-15-13-12-26-27-19-17-16-18-27-24-10-6-7-9-4-8-5-23-21-3-1
	0.5 - 1	40.00	18.13	58.13	1-2-21-23-10-6-8-5-7-9-4-24-27-19-17-16-18-27-26-12-13-14-15-11-25-21-3-1
4-5	0.0 - 1	17.7	17.7	35.4	1-2-20-22-8-7-4-9-6-5-23-26-18-16-15-17-26-25-11-12-13-14-10-24-20-3-1
4-6	0.0 - 0.5	46.57	13.71	60.28	1-2-18-22-11-14-15-13-12-23-24-16-24-21-10-6-7-9-4-8-5-20-18-3-1
	0.6 - 1	44.30	13.90	58.2	1-2-18-20-10-6-8-5-7-9-4-21-24-16-24-23-12-13-14-15-11-22-18-3-1
4-7	0.0 - 1	13.5	13.5	27	1-2-17-19-8-7-4-9-6-5-20-23-15-23-22-11-12-13-14-10-21-17-3-1
5-1	0.0 - 0.3	42.86	23.45	66.31	1-2-27-32-15-14-11-16-13-12-33-36-25-23-22-24-36-30-10-6-8-5-7-9-4-30-35-18-19-20-21-17-34-27-3-1
	0.4 - 0.7	37.87	23.89	61.76	1-2-27-34-18-19-20-21-17-34-32-15-14-11-16-13-12-33-36-25-23-22-24-36-30-10-6-7-9-4-8-5-5-29-27-3-1
	0.8 - 1	37.00	24.26	61.26	1-2-27-29-10-6-8-5-7-9-4-30-36-25-23-22-24-36-33-12-11-16-13-14-15-32-34-18-19-20-21-17-34-27-3-1
5-2	0.0 - 0.3	43.43	19.22	62.65	1-2-24-29-15-14-11-16-13-12-30-27-10-6-8-5-7-9-4-27-33-22-33-32-18-19-20-21-17-31-24-3-1
	0.4 - 0.7	38.44	19.67	58.11	1-2-24-31-18-19-20-21-17-31-29-15-14-11-16-13-12-30-33-22-33-27-10-6-7-9-4-8-5-26-24-3-1
	0.8 - 1	37.63	20.03	57.66	1-2-24-26-10-6-8-5-7-9-4-27-33-22-33-30-12-11-16-13-14-15-29-31-18-19-20-21-17-31-24-3-1
6-1	0.0 - 1	54.4	24	78.4	1-2-28-33-15-14-11-16-13-12-34-38-26-38-31-10-6-8-5-7-9-4-31-37-25-23-22-24-37-36-18-19-20-21-17-35-28-3-1
7-1	0	71.24	31.50	102.7	1-2-29-38-23-22-39-35-14-15-11-16-13-12-35-32-10-6-8-5-7-9-4-32-37-18-19-20-21-17-36-42-26-27-42-40-24-25-40-29-3-1
	0.1	46.18	31.60	77.78	1-2-29-38-23-22-39-32-10-6-7-9-4-8-5-31-34-15-14-11-16-13-12-35-43-27-26-43-37-18-19-20-21-17-36-40-24-25-40-29-3-1
	0.2	45.04	31.72	76.77	1-2-29-38-23-22-39-32-10-6-8-5-7-9-4-32-41-25-24-41-37-18-19-20-21-17-37-43-27-26-43-35-12-11-16-13-14-15-34-29-3-1
	0.3 - 1	39.57	33.29	72.86	1-2-29-40-24-25-41-32-10-6-8-5-7-9-4-32-39-22-23-39-37-18-19-20-21-17-36-34-15-14-11-16-13-12-35-43-27-26-42-29-3-1
8-1	0.0 - 0.3	58.70	35.68	94.39	1-2-31-42-24-25-42-44-26-27-44-40-23-22-41-34-10-6-8-5-7-9-4-34-37-14-15-11-16-13-12-37-39-18-19-20-21-17-38-46-28-29-46-31-3-1
	0.4 - 0.6	55.46	35.77	91.23	1-2-31-40-23-22-41-34-10-6-7-9-4-8-5-33-36-15-14-11-16-13-12-37-47-29-28-47-45-27-26-45-39-18-19-20-21-17-38-42-24-25-42-31-3-1
	0.7 - 0.8	54.06	35.89	89.96	1-2-31-40-23-22-41-34-10-6-8-5-7-9-4-34-43-25-24-43-39-18-19-20-21-17-39-47-29-28-47-45-27-26-45-37-12-11-16-13-14-15-36-31-3-1

Case	α	MTC ($)	GTC ($)	TC ($)	Route
	0.9 - 1	48.85	37.46	86.31	1-2-31-42-24-25-43-34-10-6-8-5-7-9-4-34-41-22-23-41-39-18-19-20-21-17-38-36-15-14-11-16-13-12-37-47-29-28-47-45-27-26-44-31-3-1
9-1	0	86.23	40.4	126.6	1-2-35-49-30-31-49-45-27-26-46-38-10-6-8-5-7-9-4-38-44-25-23-22-24-44-41-14-15-11-16-13-12-41-43-18-19-20-21-17-42-51-32-33-51-47-28-29-47-35-3-1
	0.1 - 0.4	58.13	40.42	98.55	1-2-35-45-27-26-46-38-10-6-8-5-7-9-4-38-44-25-23-22-24-44-41-14-15-11-16-13-36-41-52-33-32-52-50-31-30-50-43-18-19-20-21-17-42-47-28-29-47-35-3-1
	0.5 - 0.7	56.25	41.22	97.47	1-2-35-45-27-26-46-43-18-19-20-21-17-42-40-15-14-11-16-13-12-41-52-33-32-52-50-31-30-50-44-25-23-22-24-44-38-10-6-8-5-7-9-4-38-48-29-28-47-35-3-1
	0.8 - 1	55.16	42.2	97.36	1-2-35-47-28-29-48-38-10-6-8-5-7-9-4-38-44-25-23-22-24-44-46-26-27-46-43-18-19-20-21-17-42-40-15-14-11-16-13-12-41-52-33-32-52-50-31-30-49-35-3-1
10-1	0	75.96	40.91	116.9	1-2-36-47-28-27-48-46-26-46-42-14-15-11-16-13-12-42-45-25-23-22-24-45-39-10-6-8-5-7-9-4-39-44-18-19-20-21-17-43-51-31-32-51-53-33-34-53-49-29-30-49-36-3-1
	0.1	65.5	40.93	106.43	1-2-36-47-28-27-48-45-25-23-22-24-45-39-10-6-8-5-7-9-4-39-46-26-46-42-14-15-11-16-13-12-42-54-34-33-54-52-32-31-52-44-18-19-20-21-17-43-49-29-30-49-36-3-1
	0.2 - 0.4	64.59	41	105.6	1-2-36-47-28-27-48-39-10-6-8-5-7-9-4-39-45-25-23-22-24-45-50-30-29-50-46-26-46-42-14-15-11-16-13-12-42-54-34-33-54-44-18-19-20-21-17-43-51-31-32-51-36-3-1
	0.5 - 0.7	62.86	41.73	104.6	1-2-36-47-28-27-48-39-10-6-8-5-7-9-4-39-45-25-23-22-24-45-54-34-33-54-52-32-31-52-44-18-19-20-21-17-43-41-15-14-11-16-13-12-42-46-26-46-50-30-29-49-36-3-1
	0.8 - 1	62.093	42.88	105	1-2-36-49-29-30-50-39-10-6-8-5-7-9-4-39-45-25-23-22-24-45-48-27-28-48-46-26-46-42-12-11-16-13-14-15-41-43-17-20-21-19-18-44-54-34-33-54-52-32-31-51-36-3-1

The results from applying Model II support the results from Model I, namely that cases 4-2, 4-3, 4-5, 4-7, and 6-1 have a single solution. Cases 3-1, 3-2, 3-3, 4-1, 4-4, and 4-6 do not provide other optimal solutions besides the two optimal solutions in the previous experiment. However, different results are given by cases 5-1 and 5-2, where both still provide other optimal solutions at weight α, in the intervals 0.5 – 0.7 and 0.8 – 0.9, respectively.

The results also show an increase in the number of alternative solutions to the case size. This increase shows that for cases that do not have a single solution, an increase in the network structure on the number of islands and nodes will increase the variety of efficient alternative solutions.

In addition, the set of efficient solutions also shows an inverse relationship between MTC and GTC. MTC decreases as GTC increases. This is related to the discussion by Miranda et al. [24] that efforts to minimize MTC in a tour system in the archipelago zone require the development of landline connectivity between piers/ports and strategic points on an island.

Other findings can be seen in Case 10-1, where the global optimum is not only obtained when minimizing MTC. In this case, the global optimum is obtained at alpha 0.5 - 0.7. This finding indicates that MTC minimization cannot be used as a reference for TC minimization in cases with many nodes and islands.

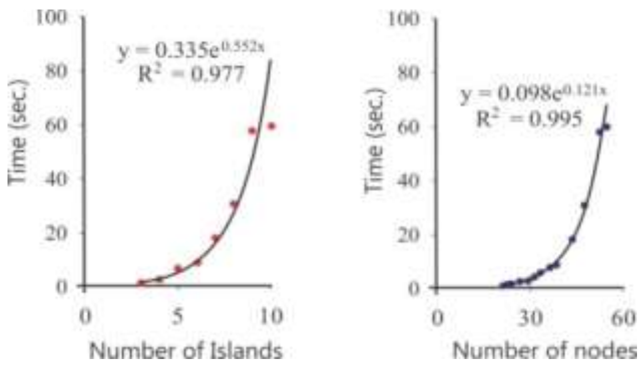


Figure 3. Computing Time Graph

Figure 3 depicts graphs between the model computing time of all cases against the number of islands and nodes. Both graphs show increasing time trends for the number of islands and nodes. Based on the exponential trend line, the number of nodes has a more significant influence with R^2 of 0.995 compared to the number of islands (R^2 of 0.977). If y represents time and x represents the number of points, then the relationship between the two can be formulated as $y = 0.098e^{0.121x}$.

4. CONCLUSIONS

The design of this model can be used to solve tour route planning problems by considering bi-objective cost minimization, either MTC, GTC, or with both priority weights. The first model was developed to prioritize one of the cost components without considering other alternative solutions. This model is suitable for situations with clarity on which route should be prioritized, sea or land. The second model was developed to explore other alternative solutions that can be considered. This model suits situations where the initial priority has yet to be discovered.

Based on the tests, the model adapts to a given case. The recommended optimal solution can be formed either singly or not. Two significant findings that can be given include: (1) for cases that do not have a single solution, increasing the network structure on the number of islands and nodes will provide an increase in the variety of efficient alternative solutions, and (2) efforts to minimize MTC in the island zone have an impact on reducing total costs but does not mean minimizing total costs.

The weakness of this model is in handling cases with a large number of islands and nodes. In further research, the model can be developed with a more practical programming approach so that it can solve cases with many nodes in an efficient time. Apart from that, the development is expected to consider the selection of types and departure schedules of public transportation modes, queuing or loading and unloading times at ports, and accommodation availability.

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