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A new model of pavement maintenance, rehabilitation and reconstruction considering multimodal network development

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Acknowledgments:

This work was supported in part by Institut Teknologi Bandung through ITB research grant (PN-2019).

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Declaration of interest :
Declarations of interest: none

This paper can be referred as below:

Zukhruf, F., Balijepalli, C., Frazila, R.B., Nugroho, T.S., Burhani, J.T. (2022) A new model of pavement maintenance, rehabilitation and reconstruction considering multimodal network development, *Engineering Optimisation*, https://doi.org/10.1080/0305215X.2022.2061477

A new model of pavement maintenance, rehabilitation and reconstruction considering multimodal network development

Abstract

Developing a multimodal transportation network to improve traffic efficiency gains extensive interest from researchers. Paradigm shift of road users to other modes of transport potentially saves travel related costs. In particular, shifting of freight traffic away from roads may reduce the deterioration of pavement, which influences the decisions related to pavement maintenance, rehabilitation, and reconstruction requirements. However, there is little evidence elaborating the impact of the shifting phenomena on the road maintenance requirements. This article presents a new highways agency focused model that integrates pavement maintenance, rehabilitation, and reconstruction decisions with multimodal transportation development involving railway and seaway routes. The model is presented within an optimisation framework and illustrates the application to a real-life case study. A greedy heuristic is modified by incorporating a threshold-based strategy, aligning the model with the highways agencies workflow, bringing with it the benefits that the optimisation offers.

Keywords: *Pavement maintenance rehabilitation and reconstruction model; Multimodal network development; Traffic assignment; Greedy Heuristics; Threshold-based strategy*

1. Introduction

In recent decades, there has been an emphasis for freight to use the railway, sea transportation, and inland waterways rather than depending heavily on road transport (European Commission, 2001). The shifting to a multimodal transportation network (MTN) aims to reduce transport emissions (Jiang *et al.*, 2020; Ziaei and Jabbarzadeh, 2021) and traffic congestion (Dantsuji *et al.*, 2021). A considerable number of studies address the MTN development, which typically estimate the user benefits, viz., the user savings of travel time (Yamada *et al.*, 2009), the surplus increment of supply chain actors (Yamada and Zukhruf, 2015), and/or the reliability of travel time (He *et al.*, 2021). Besides the road users, highways agencies are the other stakeholders who potentially benefit from the MTN development. It is the case since the development of MTN could shift the freight to a non-road-based mode resulting in a slower pavement deterioration. The slower deterioration of pavements might reduce the pavement maintenance, rehabilitation, and reconstruction (MR&R) cost in which the highways agency gains benefit directly. Hence, a comprehensive investigation needs to be done to elaborate on the impact of MTN development on the MR&R program.

The MR&R program has been perceived as a vital aspect of maintaining road network efficiency. For many years, numerous models have been proposed to seek a suitable MR&R program, developed in terms of a single segment- and/or network-level approaches. Single segment-level MR&R problems focus on the strategy required for maintaining a segment by considering its deterioration mechanism (Bai *et al.*, 2015; Deshpande *et al.*, 2010; Lee and Madanat, 2014). On the contrary, the MR&R network-level problems view the deterioration problem comprehensively for the whole of a network. Because highways agencies deal with the entire road network under their jurisdiction, the network-level approaches gain increasing popularity (Chootinan *et al.*, 2006; Lee and Madanat, 2015, 2017; Santos *et al.*, 2017).

Due to its advantage that it can theoretically optimise the MR&R decision with a constrained budget utilisation, the optimisation model for the MR&R program has been applied in numerous studies (Chu and Huang, 2018; Fwa *et al.*, 1994). However, the optimisation approach, in general, is not a well-accepted method by the highways agencies in practice (Chu and Huang, 2018). It is the case since, practically, the highways agencies adopt a *threshold-based strategy* for planning the MR&R program that is suitable with their workflow. This strategy means, a pavement receives a certain MR&R action when its condition falls below certain thresholds based on expert knowledge (Khurshid *et al.*, 2010). However, these thresholds determined through expert judgment may lead to obtaining a non-optimal solution to the MR&R program. Thus, there is a need to combine the best of both, and to gain the synergetic advantage, in this article, an integrated model of the MR&R optimisation embedded with a threshold-based strategy is proposed. The combination expectantly provides an optimal MR&R program with due consideration given to the agency's workflow.

Despite their popularity, network-level MR&R programs face a challenging issue, namely, the estimation of future conditions that may lead to inaccuracies. The inaccuracy may be contributed by the deterioration model (Durango and Madanat, 2002) as well as the inputs to the model (e.g., traffic load). Several studies have proved that the traffic load has a major contribution to pavement deterioration (Manoharan *et al.*, 2021; Mazari and Rodriguez, 2016). Traffic load is also affected by the route choice of road users. Thus, the incorporation of a traffic assignment model into an MR&R model is important for representing a reasonable pattern of traffic load. Several studies have incorporated traffic assignment within their MR&R models, where the equilibrium assignment model only considered single user class in the road transportation network (RTN) (see, for example, Chu and Chen, 2012; Chu and Huang, 2018; Hajibabai *et al.*, 2014; Liu *et al.*, 2020). However, as it is mentioned by Chu and Chen (2012), the assumption of a single-user class might produce an impractical estimation of pavement deterioration. Hence the consideration of multiclass traffic assignment is the logical step to progress the research in this area. The involvement of multiclass users can also provide an opportunity to explore the impacts of MR&R program on traffic users.

Taking together the issues introduced above, a combined model is presented for handling the network-level MR&R programs whilst explicitly considering the impact of MTN development. Using a multimodal traffic assignment technique, the development of MTN is explicitly considered. The proposed model is then constructed within the framework of a bilevel optimisation problem that aims to minimise the international roughness index (IRI) at the upper level. A greedy heuristic procedure is modified by adding a threshold-based strategy for solving the optimisation problem of the MR&R program. Meanwhile, the multimodal traffic assignment problem is solved at the lower-level. The estimated traffic is converted to equivalent standard axle loads (ESAL), an input required by the upper-level problem. This article also considers multiclass traffic flow to develop a better understanding of the impact of MTN users on MR&R, and vice versa. The proposed model allows the highways agencies to calculate the indirect benefits due to MTN development (e.g., decrease in travel time, operation costs, etc.) as well as the direct benefits, namely, the saving to the MR&R cost.

The remainder of the article is prepared as follows. In the second section, the literature is reviewed to position our research identifying its contribution. The modelling framework is described in the third section, which is followed by the elaboration with numerical examples in the fourth section. Finally, in the last section, the article 's methodologies, results, and analyses are summarised.

2. Literature review

The research on MR&R program has two main streams of studies: (i) single segment-level studies, and (ii) network-level studies. At the single segment level, a rich body of literature has been noted. Friesz and Fernandez (1979) initially handled the treatment of a single segment as part of their MR&R program based on a continuous-states formulation by utilising the optimal control theory. However, the issue of discontinuity of pavement trajectory is noted. Tsunokawa and Schofer (1994) apply a trend curve based optimal control model. Their work is further extended to handle treatments such as resurfacing, resealing and reconstruction though still for single segments (Rashid and Tsunokawa, 2012). The consideration of discrete state has also been proposed in studies involving memoryless deterioration process for single treatments (Carnahan *et al.*, 1987; Fwa *et al.*, 1994) and multiple treatments (Madanat, 1993; Madanat and Ben-Akiva, 1994). There are also several efforts to tackle the history-dependent deterioration process (Deshpande *et al.*, 2010; Tsunokawa *et al.*, 2002, 2006). Although the network-level studies comprise a more complex problem than the single-level ones, they gather growing interest due to their 'close to reality' nature. Several studies, ranging from a simple model to a more complicated one, were conducted. A simple model typically assumes that the deterioration process is memoryless (Chan *et al.*, 1996; Fwa *et al.*, 1996), and it only includes a single treatment for maintaining the pavement condition (Ouyang, 2007; Ouyang and Madanat, 2004). In contrast, the latter models pay attention to the history-dependent deterioration involving multiple treatments (Chu and Chen, 2012; Lee *et al.*, 2016).

In terms of the network-level problem, four main strategies are applied to solve the MR&R problem: (i) optimisation-based strategy, (ii) worst-first-based strategy, (iii) best-first-based strategy, and (iv) threshold-based strategy. The *optimisation-based strategy* employs mathematical/simulation methods for generating an optimal solution of the MR&R program (Chu and Huang, 2018). The *worst-first-based strategy* handles the pavement with the worst condition and then follows up by tackling the road with a better condition until the budget allocation is run out (Abaza *et al.*, 2004). In contrast with the worst-first strategy, the *best-first-based strategy* starts the MR&R action from the pavement that has the best condition, which is then moved to the poorer one until the budget is exhausted (Chu and Huang, 2018). Finally, the *threshold-based strategy* decides the MR&R action based on the pavement condition by comparing the existing condition with some predetermined thresholds.

Due to its suitability to the highways agencies' workflow, the threshold-based strategy gained significance and has been extensively studied in the literature (Chu and Huang, 2018). The threshold structure has been investigated for a single segment by Ouyang and Madanat (2006) and for the network level by Lee *et al.*, (2016). Liu *et al.*, (2020) consider the threshold-based strategy for evaluating the performance of an eco-based MR&R model. They found that the threshold-based strategy could efficiently restore the pavement roughness with a relatively small budget. However, they also mentioned the ineffectiveness of budget spending in the threshold-based strategy, which was also raised by Chu and Huang (2018). When applying the threshold-based strategy, the budget could be redundant when all pavements of a network are in good condition. In contrast, the budget might not be sufficient when the pavement conditions are bad or even worse over many parts the network. However, optimisation-based strategy for MR&R programming potentially provides the much needed efficiency of budget utilisation (Chu and Huang, 2018; Lee and Madanat, 2015; Ye *et al.*, 2018). Therefore, our study seeks to incorporate the threshold-based strategy within an optimisation framework, bringing together the best of both to generate an efficient solution to MR&R program.

Pavement deterioration substantially depends on the traffic load on a road link (Manoharan *et al.*, 2021). Thus, previous studies explicitly considered the interactions of traffic load on the network and MR&R program in their models (Chu and Chen, 2012; Chu and Huang, 2018; Hajibabai *et al.*, 2014; Liu *et al.*, 2020). However, they were limited to incorporating RTN problem modelling a single user class of traffic assignment. The literature has mentioned that the development of MTN can shift the traffic flow away from the roads and can improve the performance of RTN (Dantsuji *et al.*, 2021; Jiang *et al.*, 2020; Ziaei and Jabbarzadeh, 2021). Several studies have also been conducted for developing MTN in order to improve the RTN's efficiency (Yamada *et al.*, 2009), to increase the supply chain surpluses (Yamada and Zukhruf, 2015), to enhance reserve capacity (Zheng *et al.*, 2020), or to minimise the carbon dioxide emissions (Yang *et al.*, 2021). However, little evidence is available thus far elaborating the MTN's impact on the MR&R program, which is the main focus of this article.

The solution techniques to solve the optimisation problem involved can be divided into exact solution methods and approximate solution methods. However, since the exact solution-based approaches require extensive computation resources, growing preference is noted for the approximate solution-based approaches (Naseri *et al.*, 2020). The approximation-based methods usually rely on heuristics (e.g., greedy-heuristics) or metaheuristics (e.g., genetic algorithm, tabu search). Ouyang and Madanat (2004) applied the exact solution-based method and compared the outcomes with the greedy-based approach for handling the MR&R program. They found that greedy heuristics could offer a good solution with faster computational times. Zhang et al. (2017) also found that greedy heuristics are much more efficient in computational resources for single-level and network-level problems. The approximation approaches become more prominent when tackling large-scale problems. Hafez et al. (2018) and Naseri et al. (2020) solved large-scale problems involving 85 and 103 segments, respectively, using approximate methods. The size of the problem is even larger in our case, and thus, an approximate solution-based method is more preferable .

The main contributions made by this article are two-fold: Firstly, it contributes to the literature by proposing a new model of MR&R program integrated with a multimodal traffic assignment. The integration potentially brings a better understanding of how the development of MTN affects the MR&R program. Secondly, a highways agency focused threshold-based strategy is applied within an optimisation framework ensuring efficient utilisation of funds, thus, reaping the benefits of both approaches. Finally, a large-scale problem with a real-life MTN is presented to illustrate applicability of the proposed model, which also helps improving the understanding in setting up and solving large scale problems.

3. Modelling framework

This section describes the modelling framework for integrating the MR&R programs with a multimodal traffic assignment (see Figure 1). We include an IRI-based measure as the objective function by considering budget constraints. A greedy heuristic is utilised for deciding the optimal pavement maintenance program by maximising the difference in IRI *with* and *without* MR&R action. The MR&R program chosen thus affects the IRI, which subsequently influences road users' vehicle operating costs. Considering the generalised travel costs on MTN, the OD demand is then assigned to the MTN, which results in the traffic flows on the seaway, railway, and roadway. The traffic on the roadways is then converted into traffic loads for predicting the pavement condition (i.e., IRI). The expected pavement condition is used as input for deciding on the MR&R program. This process is iterated until the end of a predetermined time horizon. The multimodality means that it considers not only the road-based modes but also the rail- and sea-based modes. Due to different characteristics of users, this article classifies the users as the *passenger* and the *freight* users in which each user can use any of the available modes. In other words, both passenger and freight users can use any modes that are available on the paths connecting each origin with each destination. Each mode is available on a set of predetermined network links with specific characteristics such as length, flow capacity, speed, loading/unloading capacity and travel fare (or freight charges). The demand is then assigned to the MTN based on user's route choice, which accounts for travel costs affected by travel time, travel fare and vehicle operating costs. The multimodal multiuser traffic assignment then provides the flow on the link by mode and by class of user.

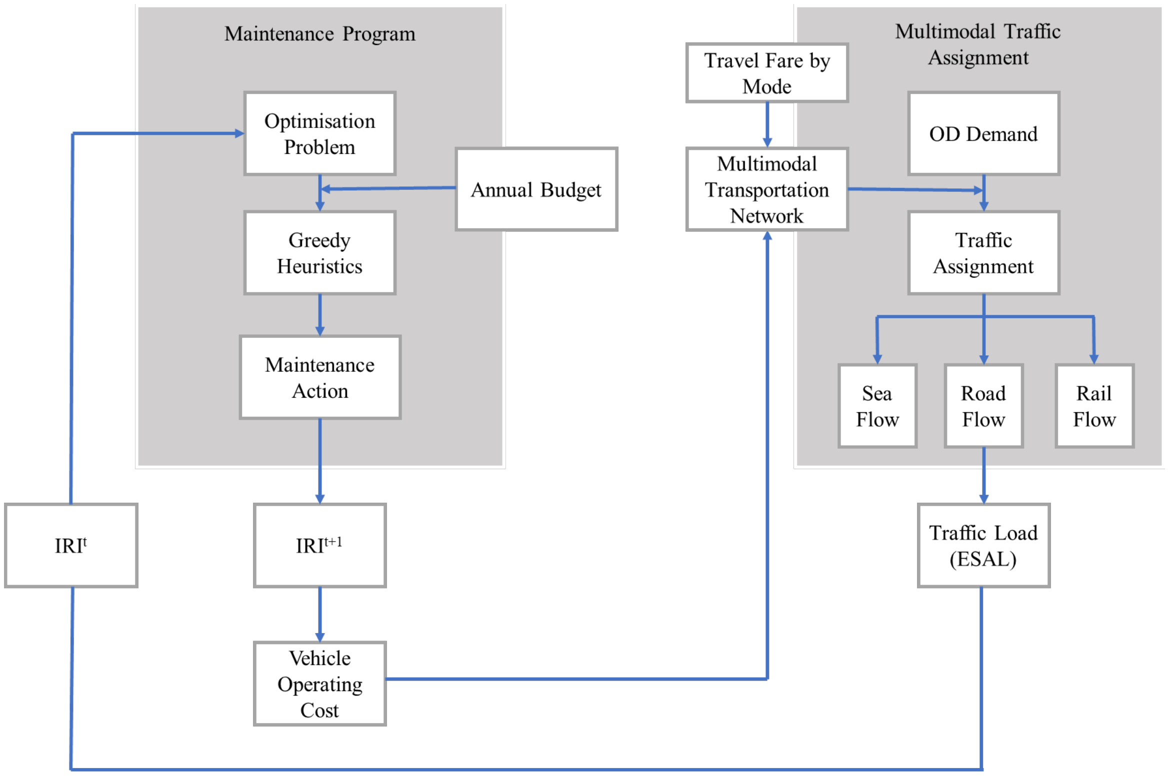
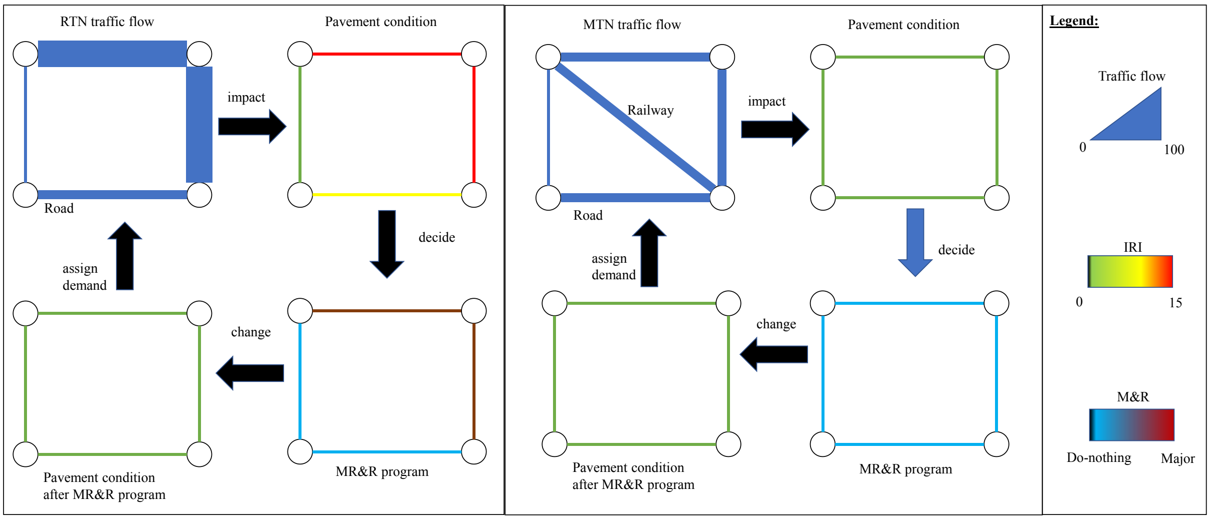


Figure 1: The framework of MR&R program with multimodal traffic assignment

The flow on the road as a result of multimodal traffic assignment is converted further to standardised axle loads. The load is used as an input for estimating the deterioration of the pavement. The pavement condition is described by IRI (in the units of *m*/*km*) that deteriorates over a period of time as a function of the load repetitions. The IRI value in the current time period depends on the value of IRI in the previous time period, the age of the pavement, and the cumulative axle load. In contrast with the earlier studies that only evaluated the RTN, our study can provide a more realistic result given the consideration to MTN development. As the development of MTN might shift the traffic flow to the seaway and/or railway, the pavement deterioration on the RTN might be slower, and thus, possibly reduces the annual cost of the MR&R program (see Figure 2 – thickness of lines indicates traffic load, and the colour indicates the condition). Therefore, the highways agency involved will have a broader perspective of the situation with MTN development, not only from the time savings concerned (Yamada *et al.*, 2009), but also from the potential savings to the MR&R cost. This impact cannot be investigated without the integration of MTN into the MR&R model, which is not available in the previous literature.



a) MR&R program without MTN consideration   b) MR&R program with MTN consideration

Figure 2: Illustration of interaction between traffic assignment, pavement condition, and MR&R program *with* and *without* MTN

For improving the pavement condition, five different activities of MR&R are considered as in Fani *et al.*, (2020), namely, *reconstruction* (i.e., replacement of entire pavement structure), *medium rehabilitation* (i.e., thick overlay), *light rehabilitation* (i.e., thin overlay), *preventive maintenance* (i.e., fog seal, slurry seal), and *do-nothing* action (i.e., without any maintenance actions). The cost of implementing such actions is relative to the road dimensions (length, width), where the reconstruction action incurs the highest cost per unit area than the others. For deciding the MR&R action, the model also includes annual budget allocation, which is treated as a constraint in the optimisation problem. A greedy heuristic is proposed for solving the optimisation problem by adding the threshold-based strategy. This strategy is embedded within the greedy algorithm to improve the effectiveness of MR&R decisions. Furthermore, the implementation of MR&R action changes the pavement condition that simultaneously adjusts the vehicle operating cost (VOC). The updated VOC and other travel costs are utilised for re-assigning the user demand to the TN. This process is iterated until the end of a predetermined time horizon, as illustrated in Figure 1 shown earlier.

3.1. Multimodal traffic assignment

This section describes the multimodal traffic assignment, which includes multiclass users, multiple modes, and the interplay between the modes. The model treats the freight and passengers as multiclass users, where route choice is carried out simultaneously (Yamada *et al.*, 2009).

The MTN is represented by graph [N, A], where N and A describe the set of nodes and links, respectively. The nodes denote crossings, junctions, transhipment terminals, and OD locations (i.e., centroids) which are all connected by the links. Each OD pair has different pathways, consisting of a combination of roadway, railway, seaway, transhipment, and centroid link, which is expressed by Equation (1).

$$A = A_{road} \cup A_{rail} \cup A_{sea} \cup A_{transhipment} \cup A_{OD} \quad (1)$$

Centroids are used to represent the origins and destinations (ODs), where it only holds the aggregate demand information (i.e., the number of persons and the amount of goods in tonnes). The user demand that is transported between OD is defined in the demand matrix for each user class-k (i.e., D^k). The transhipment provides the interconnection among modalities (He *et al.*, 2021; Yamada *et al.*, 2009), which incorporates the loading/unloading processes (see Figure 3).

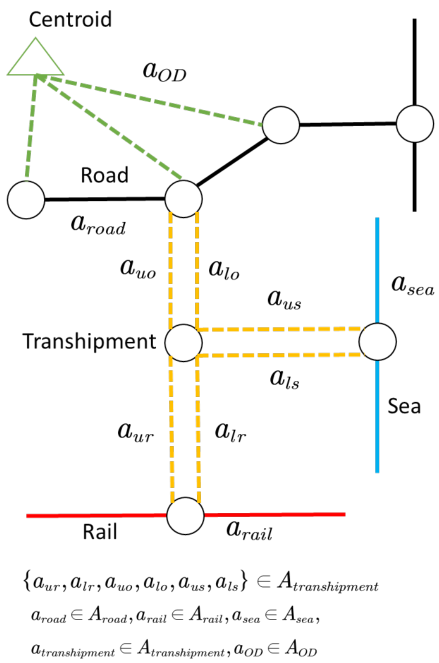


Figure 3: Multimodal transportation network representation

Note: a_{ur}, a_{lr} : unloading, loading link for rail mode, respectively; a_{uo}, a_{lo} : unloading, loading link for road mode, respectively; a_{us}, a_{ls} : unloading, loading link for sea mode, respectively; $a_{road}, a_{rail}, a_{sea}, a_{OD}$: link used by road, rail, sea mode, and centroid, respectively.

Assume p is a path consisting of a set of links, which connects an OD pair. Let W represent the set of OD pairs, then the set of paths connecting the particular pair of OD-w is symbolised by P_w. The traffic flow of class-k in the link–a (i.e., $f_a^k, \forall a \in A$) is indicated by summing class-k flow of all paths (i.e., x_p^k) using link–a:

$$f_a^k = \sum_{p \varepsilon P} x_p^k \vartheta_{ap}, \ \forall a \in A, \ k \in K \quad (2)$$

where $\vartheta_{ap} = 1$ if link–a is contained in the path p, or, $\vartheta_{ap} = 0$ otherwise. Then the travel demand of class-k for OD pair-w (i.e., d_w^k) must conserve by satisfying the relationship:

$$d_w^k = \sum_{p \in P_w} x_p^k, \ \forall w \in W, \ k \in K \quad (3)$$

Each link is specific to a predetermined mode, the vehicle numbers on link-*a* for each user-*k* (i.e., q_a^k) is obtained by dividing the traffic flow of class-*k* on link–*a* with the capacity of mode of class-*k* on the link–*a* (i.e., l_a^k), as stated by Equation (4). In the case of goods carrying vehicles, this article uses the '*practical load'* terminology for defining the modal capacity. This terminology facilitates capturing the phenomena of overloading of trucks that carry goods beyond the stated capacity by the manufacturers.

$$q_a^k = \frac{f_a^k}{l_a^k} \quad \forall a \in A,\ k \in K \tag{4}$$

The travel time includes the journey time on a link and the delay time for obtaining the service, namely, the loading/unloading time for freight users and waiting time for the passengers. The travel time on the link-*a* by class user-*k* (i.e., u_a^k) is constructed based on the Bureau of Public Roads (BPR) function, which allows the interaction between capacity (i.e., ζ_a) and traffic flow on link-*a* (see Equation (5)). Because the model considers multimodal links and terminal links, which have different characteristics, the parameters are set as appropriate (Yamada *et al.*, 2009). For estimating the monetary values, the travel time is multiplied by the unit value of time, in which the freight user has a bigger unit value than the passenger user.

$$u_a^k(f_a) = u_{0a}\left(1 + \phi_1 f_a + \phi_2\left(\frac{f_a}{\zeta_a}\right)^{\phi_3}\right) \tag{5}$$

where, ϕ_1, ϕ_2, ϕ_3 denotes the predefined constants, and u_{0a} is the free flow travel time by link *a*. The VOC is associated with out-of-pocket costs for operating the vehicle, namely, fuel, tyre wear, vehicle repair, and oils. These spendings on VOCs are related to the pavement condition and the travel speed (Chatti and Zaabar, 2012). Equation (6) illustrates the consideration of VOC (i.e., v_a^k), where b_1, b_2, b_3, b_4 and $d_{fuel}^k, d_{tyre}^k, d_{oil}^k, d_{rep}^k$ denote the constant monetary spending per km, and the operation cost function of class *k* for fuel, tyre, vehicle maintenance and repair, and, oils, respectively. The travel fare/freight charge is determined in advance. The fare is assigned to each link, set differently for each user class, each type of mode, and each type of link (i.e., terminal and mode).

$$v_a^k = b_1 d_{fuel}^k(y_a, s^k) + b_2 d_{tyre}^k(y_a, s^k) + b_3 d_{oil}^k(y_a, s^k) + b_4 d_{rep}^k(y_a, s^k) \tag{6}$$

To decide the route, passenger users depend on the travel time value, the vehicle operating cost when they ride their own vehicle, and the travel fare when using the railway or the seaway. Equation (7) then represents such assumptions that are formulated using a simple linear combination.

$$\eta_p^{k_1} = \alpha^{k_1} \sum_{a \in A} \vartheta_{ap} u_a^{k_1}(f_a) + \sum_{a \in A} \vartheta_{ap} e_{1a} v_a^{k_1}\left(y_a, s_a^{k_1}\right) + \sum_{a \in A} \vartheta_{ap} e_{2a} m_a^{k_1}, \quad \forall p \in P, k_1 \in K \tag{7}$$

where:

$\eta_p^{k_1}$: generalised travel cost of passenger class user on path–p.

α^{k_1} : time value of passenger class user.

u_a : travel time on link-a.

e_{1a} : binary variable that value 1 if $a \in A_{road}$ and 0 for otherwise.

e_{2a} : binary variable that value 1 if $a \in A_{sea}$ or $a \in A_{rail}$ and 0 for otherwise.

$v_a^{k_1}$: VOC of passenger class user when use link–a.

$s_a^{k_1}$: travel speed of passenger class user when use link–a.

$m_a^{k_1}$: travel fare of passenger class user when use link–a.

y_a : IRI of link–a.

In the case of freight user class, it is assumed that the goods owner only considers the travel time value and the travel fare. Therefore, the generalised cost is only a function of two variables, as described by Equation (8):

$$\eta_p^{k_2} = \alpha^{k_2} \sum_{a \in A} \vartheta_{ap} u_a^{k_2}(f_a) + \sum_{a \in A} \vartheta_{ap} m_a^{k_2}, \ \forall p \in P, k_2 \in K \tag{8}$$

$\eta_p^{k_2}$: generalised travel cost of freight class user on path–p.

α^{k_2} : time value of freight class user.

For each class k, for each OD pair-w, and for each path $p \in p_w$, there is a travel disutility as a function of the path-flow pattern. The traffic flow is regarded in equilibrium if the following condition holds:

$$\eta_p^k(f^*) \begin{cases} = \lambda_w^k \text{ if } x_p^{k*} > 0, \\ \geq \lambda_w^k \text{ if } x_p^{k*} = 0, \end{cases} \ \forall p \in P, k \in K, w \in W \tag{9}$$

where λ_w^k is the travel disutility, whose value is not previously known. As can be inferred by Equation (8) if the path travel cost is higher than the travel disutility, the flow on that path is zero. On the other hand, the path flow is greater than or equal to zero when the travel cost is equal to the travel disutility.

This article utilises the diagonalisation method within the solution algorithm to handle multimodal traffic assignment (Sheffi, 1985). Essentially, this method keeps the interaction effect constant while solving the assignment problem by a descent direction algorithm. The advantage of this method is that it can be applied for both fixed and elastic demand cases (Yang and Huang, 2005). When updating the flow and the demand of one user class in the next iteration, the other user class flow and demand is held constant. The assignment iterations continue until no significant changes in the flows and demand for all user classes are obtained.

3.2 Optimisation problem

The objective function of optimisation problem intends to maximise the difference in IRI *without*- and *with*- the MR&R program within the time horizon (see Equations (10) and (11)). We choose IRI-based measure as it is commonly applied by highways agencies to decide on the maintenance program. The IRI-based measure also allows us to quickly investigate and compare the results of the pavement maintenance program without needing further inputs. Equations (12) – (16) describe the annual budget restriction for maintenance programs. Equation (17) explains that a single MR&R action only handles each pavement in a period. Equations (18) – (19) show the deterioration formula for predicting the IRI that is influenced by traffic flow, pavement age, and the MR&R action.

$$\max \sum_{t=1}^{T} \Delta IRI_t \tag{10}$$

$$\Delta IRI_t = \sum_{a \in A_{road}} \left(\delta_{1at} - \sum_{i=1}^{I} \theta_{iat} \delta_{iat} \right) \tag{11}$$

$$\sum_{a \in A_{road}} \sum_{i=1}^{I} c_i \theta_{iat} \leqslant bud_t; \forall t = 1, ..., T, \tag{12}$$

$$\sum_{a \in A_{road}} c_{2at} \theta_{2at} \leqslant bud_t; \forall t = 1, ..., T \tag{13}$$

$$\sum_{a \in A_{road}} c_{3at} \theta_{3at} \leqslant bud_t; \forall t = 1, ..., T \tag{14}$$

$$\sum_{a \in A_{road}} c_{4at} \theta_{4at} \leqslant bud_t; \forall t = 1, ..., T \tag{15}$$

$$\sum_{a \in A_{road}} c_{5at} \theta_{5at} \leqslant bud_t; \forall t = 1, ..., T \tag{16}$$

$$\sum_{i=1}^{I} \theta_{iat} = 1; \forall t = 1, ..., T, \ a \in A_{road}, \tag{17}$$

$$\delta_{iat} = \theta_{iat} \left(h_i n_{at} \left(f_a^{*k}, e^k \right) + u_i g_{at} + r_i y_{a,(t-1)} \right); \forall t = 1, ..., T, a \in A_{road} \tag{18}$$

$$\sum_{i=1}^{I} \delta_{iat} = y_{at}; \forall t = 1, ..., T,\ a \in A_{road} \tag{19}$$

where,

θ_{iat} : binary variable whether MR&R action–i is selected for road segment–a in time period–t.

δ_{iat} : IRI of road segment–a at time period–t if action–i implemented.

c_{iat} : cost for implementing MR&R action–i on segment-a at time period–t, where i=1,2,3,4,5 represents do-nothing action, preventive maintenance, light rehabilitation, medium rehabilitation, and reconstruction.

bud_t : available budget at time period–t.

h_{1i} : coefficient of the exogenous variable if action–i implemented.

h_{2i} : coefficient of the exogenous variable of pavement age if action–i implemented.

h_{3i} : coefficient of the exogenous variable of lagged IRI if action–i implemented.

n_{at} : traffic load of road segment–a in time period–t .

f_a^{*k} : equilibrium traffic flow of class k on road segment–a.

g_{at} : age of road segment–a in time period–t.

y_{at} : IRI of road segment–a at time period–t .

T : time horizon.

3.3 Solution technique for optimisation problem

The greedy heuristic-based approach is adopted for handling the optimisation problem of the MR&R program. In this article, a modified version of the greedy heuristics is proposed by incorporating a threshold-strategy for guiding the solution. Threshold strategy is widely applied for selecting MR&R actions, as it fits well with the standard workflow of highways agencies. This strategy simply entails mapping the IRI of a segment to an MR&R threshold, and then selecting an appropriate action plan based on the position of IRI within the threshold range (see Table 1). The main weakness of threshold-based strategy arises from the fact that it may seek a sub-optimal solution because it is based on individual judgement. Moreover, the standard greedy heuristic relies solely on the difference in fitness value (IRI difference *without* and *with* MR&R) which is likely to push the MR&R actions towards reconstruction more often, without paying any attention to the IRI value itself. In order to address this concern, we introduce a weighting factor to the thresholds as described further in the following paragraph.

The threshold-based strategy is combined within the greedy heuristic by introducing a weighting factor of each action-i (ϱ_{iat}). This factor multiplies the fitness value to be ranked by greedy heuristics (see Equation (20)). For instance, if the IRI of a segment is less than 4 *m/km*, based on the threshold levels defined (See Table 1), the suggested MR&R will be the preventive maintenance action. Therefore, the weighting factor for the preventive maintenance action is set equal to 2 and the rest of the actions are set equal to 1 (see Table 1). The higher value of weighting factor means that the preventive maintenance action is twice more likely to be recommended than the others. A similar set of steps is followed with the full range of IRI values between 4−8, 8−12, and more than 12. By utilising this factor, the greedy heuristics not only considers the difference in IRI between *with* and *without* MR&R action, but also takes account of the absolute value of IRI without MR&R action itself (i.e., δ_{1at}). This consideration possibly avoids the algorithm from choosing the reconstruction action which usually presents with a bigger difference than the other actions would, though inefficient from a budget perspective.

Table 1: Illustration of MR&R threshold and weighting factor

No	IRI threshold	MR&R action	Weighting factor
1	2<IRI <4	Preventive Maintenance	$\varrho_{2at}=2;\varrho_{3at},\varrho_{4at},\varrho_{5at}=1$
2	4 ≤ IRI <8	Light Rehabilitation	$\varrho_{3at}=2;\varrho_{2at},\varrho_{4at},\varrho_{5at}=1$
3	8 ≤ IRI <12	Medium Rehabilitation	$\varrho_{4at}=2;\varrho_{2at},\varrho_{3at},\varrho_{5at}=1$
4	IRI ≥ 12	Reconstruction	$\varrho_{5at}=2;\varrho_{2at},\varrho_{3at},\varrho_{4at}=1$

The general procedure for implementing the algorithm is described as **Algorithm**.

Algorithm: Greedy Heuristics with MR&R thresholds

1: Set t=1 and the initial value of IRI at segment-a (i.e., δ_{1at}) and $\theta_{iat}=0$.
2: **for** a=1 **to** $|A_{road}|$
3: **for** i=1 **to** 5
4: Calculate the estimated IRI value at segment-a for each action-i (i.e., δ_{iat})
5: Calculate Υ_{iat} for each segment-a of each action-i by considering the difference of IRI (i.e., with- and without- MR&R action) and a weighting factor (ϱ_{iat}), which is represented by Equation (20)

$$\Upsilon_{iat}=\varrho_{iat}(\delta_{1at}-\delta_{iat}) \quad (20)$$

where, the weighting factor follows Equations (21) – (26)
6: **end for**
7: **end for**
8: Set $cost$=0 and rank the Υ_{iat} in the descending order to create set Ξ,

9: Gradually select the MR&R action based on the ranking of Ξ by applying the following procedures:
10: **for** o=1 to $|\Xi|$
11: **if** $\sum_{i=1}^{5} \theta_{iat} < 1$, $a \in \Xi_o$ **then**
12: **if** $cost + c_i \leq bud_t$ then
13: $\theta_{iat} = 1$ & $cost = cost + c_i$
14: **end if** $cost + c_i \leq bud_t$ then
15: **end if**
16: **end for**
17: Update the pavement condition by applying Equation (18), then calculate the value of the objective function.
18: Set t=t+1, if t less than T goes to :2, otherwise finish the process.

The MR&R thresholds and the weighting factors need to be carefully determined, thus, this article specifies the generic formulation as follows:

$$\text{if } \delta_{1at} \leq \pi_1 \text{ then } \varrho_{1at} = j, \varrho_{2at}, \varrho_{3at}, \varrho_{4at}, \varrho_{5at} = 1 \quad (21)$$

$$\text{if } \pi_1 < \delta_{1at} \leq \pi_2 \text{ then } \varrho_{2at} = j, \varrho_{1at}, \varrho_{3at}, \varrho_{4at}, \varrho_{5at} = 1 \quad (22)$$

$$\text{if } \pi_2 < \delta_{1at} \leq \pi_3 \text{ then } \varrho_{3at} = j, \varrho_{1at}, \varrho_{2at}, \varrho_{4at}, \varrho_{5at} = 1 \quad (23)$$

$$\text{if } \pi_3 < \delta_{1at} \leq \pi_4 \text{ then } \varrho_{4at} = j, \varrho_{1at}, \varrho_{2at}, \varrho_{3at}, \varrho_{5at} = 1 \quad (24)$$

$$\text{if } \delta_{1at} > \pi_4 \text{ then } \varrho_{5at} = j, \varrho_{1at}, \varrho_{2at}, \varrho_{3at}, \varrho_{4at} = 1 \quad (25)$$

$$\pi_4 > \pi_3 > \pi_2 > \pi_1 \quad (26)$$

4. Numerical example

This section illustrates the applicability of the proposed model for programming the MR&R efficiently by considering the development of an MTN in real life. The MTN is located in the southern part of Sulawesi Island in Indonesia, which involves a network of roads, seaway links, and railway links. There are two different classes of users (i.e., passenger and freight), 19 pairs of ODs each for the freight and passenger users The road network contains 194 nodes and 476 links with a total length of 7,069 km (Figure 4a). MTN development comprises 10 seaport terminals, 12 railway stations, 9 seaway links, and 10 railway links (see Figure 4b and 4c).

The demand OD data is derived from the National Transportation Master Plan of the Indonesian Ministry of Transportation (2019). Figure 5 depicts the demand data for both passenger and freight. Note that the unit for passenger demand is persons whilst the unit for freight demand is in tonnes. The total vehicular trips for each OD for both users then will be derived by dividing the demand with the capacity of each mode as described later in this section.

In the case of RTN, the road capacities, initial IRI value, and traffic data were obtained from the Integrated Road Management System (IRMS) provided by the Ministry of Public Works and Housing of Indonesia. The deterioration variable in Equation (18) is defined further as a function of traffic load over time by Equation (27), which is adopted from Chu and Huang (2018).

$$\delta_{(1j,t+1)} = \theta_{1jt}\left(1.033 y_{jt} + 1.033^{(g_{jt}+1)} 0.085 n_{jt}\right); i = 1 \tag{27}$$

The general VOC function specified in Equation (6), is further set out as in Equations (28) – (29) for passengers and freight respectively, which are adopted from Chatti and Zaabar (2012). Table 2 shows the monetary values of passenger time, freight time which are essential for estimating the generalised costs involved.

$$\begin{aligned} v_{at}^{k_1} = {} & 0.0701 b_1\left(0.374 + 0.009 s_a^{k_1} + 0.030 y_{at}\right) \\ & + 0.001 b_2\left(0.790 + 0.003 s_a^{k_1} + 0.011 y_{at}\right) \\ & + 0.015 b_3\left(-0.056 + 0.011 s_a^{k_1} + 0.173 y_{at}\right) \\ & + b_4\left(-0.409 + 0.021 s_a^{k_1} + 0.008 y_{at}\right) \end{aligned} \tag{28}$$

$$\begin{aligned} v_{at}^{k_2} = {} & 0.124 b_1\left(-0.089 + 0.019 s_a^{k_2} + 0.044 y_{at}\right) \\ & + 0.001 b_2\left(-0.568 + 0.003 s_a^{k_2} + 0.020 y_{at}\right) \\ & + 0.021 b_3\left(-1.421 + 0.024 s_a^{k_2} + 0.243 y_{at}\right) \\ & + b_4\left(0.290 + 0.012 s_a^{k_2} + 0.043 y_{at}\right) \end{aligned} \tag{29}$$

Table 2: Cost items for the VOC and the travel time value

Items	Unit	Passenger User	Freight User
Fuel cost (b_1)	IDR per km	1,008	1,786
Tyre cost (b_2)	IDR per km	20	36
Maintenance cost (b_3)	IDR per km	600	870
Oil cost (b_4)	IDR per km	168	300
Value of time	IDR per hour	17,468	28,827

Note: 1 USD = 14235 IDR (www.Oanda.com 15 Sep 2021)

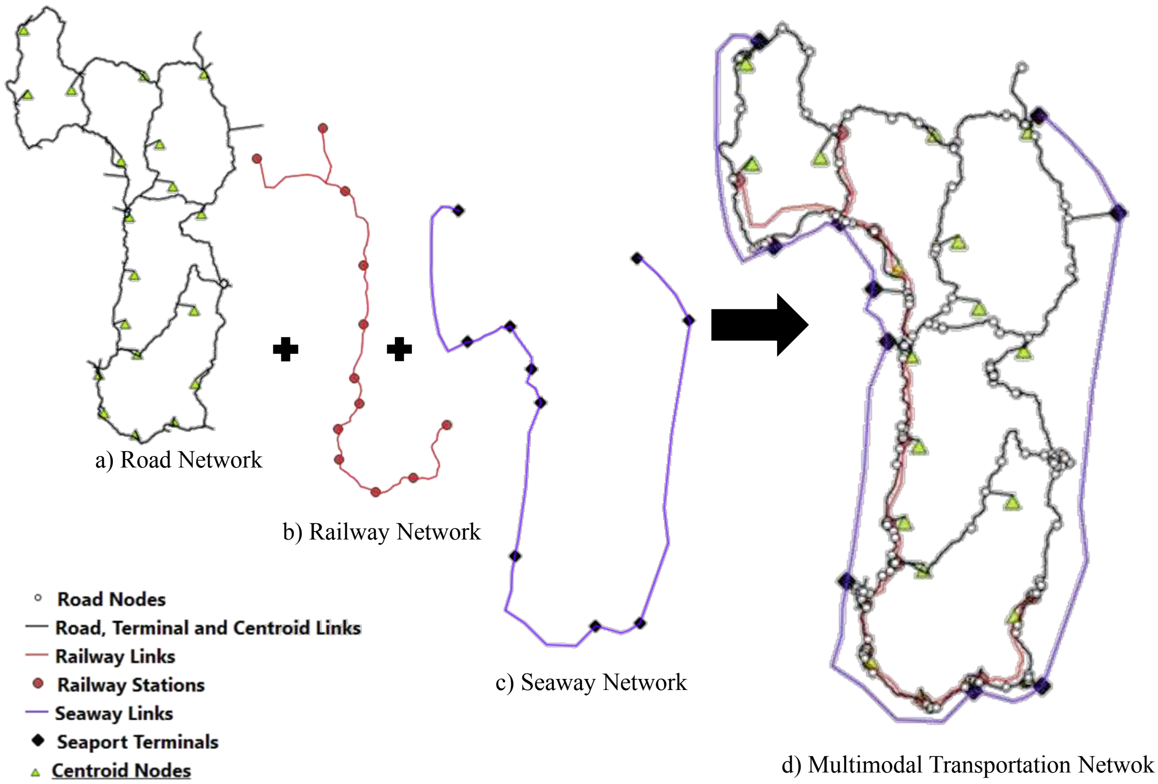


Figure 4: Test network of multimodal transportation

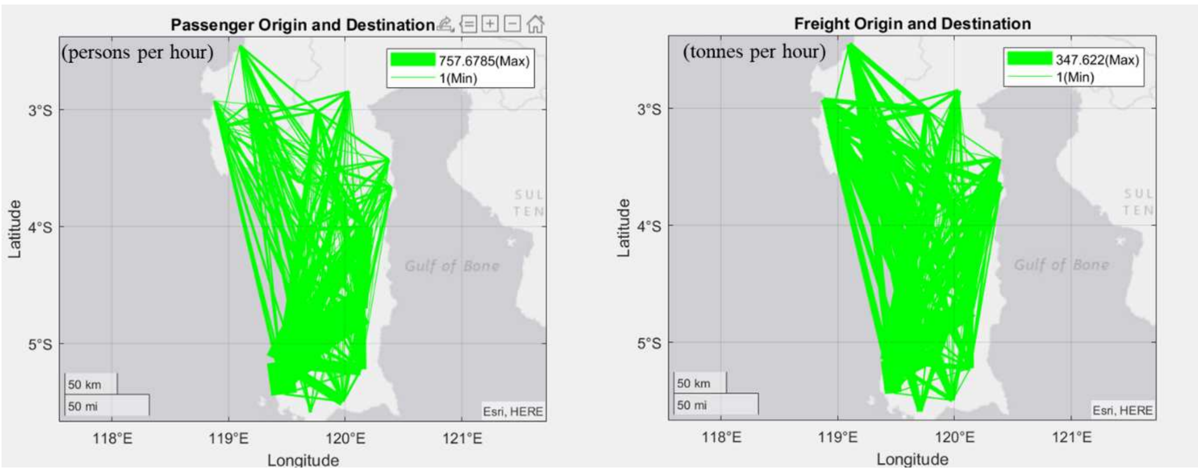


Figure 5: OD demand for test network

The MR&R actions will result in a specific IRI performance jump as shown in Table 3. These values are adopted from Fani *et al.*, (2020) and Naseri *et al.*, (2021), in which they estimated the average value of performance jump based on the works of Lu and Tolliver (2012) and Paterson (1990). The unit cost of MR&R treatment was derived from the standard cost for the MR&R of road in Indonesia (West Java Provincial Government, 2016).

Table 3: The unit cost of MR&R treatments and the expected performance jump

MR&R treatment	Unit Cost (Billion IDR/Km) *	Annual Budget (Billion IDR) **	IRI performance jump (m/km)
Do nothing	0	0	0
Preventive Maintenance	0.10	700	0.3
Light Rehabilitation	0.50	3,502	1.2
Medium Rehabilitation	1.10	7,704	2.0
Reconstruction	2.60	18,210	Restore pavement condition to IRI=1.5

* for road width 3.5 m

** total budget required to treat all the road with the related MR&R by multiplying the unit cost, length, and width of road.

To facilitate the data input, data processing and displaying results, the model is developed using the MATLAB's integrated development environment, specially developed a standalone application called, *OPTANT PJ* by the authors (Zukhruf and Frazila, 2021) (See the Appendix for details on OPTANT PJ). This application is then used for conducting the tests with the network, which is presented in the next sub-section. In summary, there are three tests as outlined here: (i) The first test is focused on applying the model to the road network without any development to the MTN. This test evaluates the performance of the proposed model that includes the threshold-based strategy; (ii) The second test incorporates the development of railway and seaway and investigates how the MTN development influences the MR&R program; and (iii) the third test considers overloading of heavy vehicles (OHV).

4.1 MR&R program without the MTN development

In the first numerical illustration, it is assumed that the seaway and railway have not been existing, and hence, the OD demand relies on using the RTN alone. The passenger users have only a car for reaching their destination. The freight users utilise a double axle truck with 16-tonnes of load (i.e., l^{k_2}) for distributing the goods. This load is set equal to the maximum allowable load in Indonesia for the truck with two axles, though in realistic conditions, trucks might be carrying higher loads than the maximum permissible load. The horizon time is set equal to five years for the analysis, where the budget constraints are determined in advance. The network is tested with five scenarios of budget availability, namely:

i) nil budget for the MR&R program (NO),
ii) preventive maintenance-based budget (PM),
iii) light rehabilitation-based budget (LR),
iv) medium rehabilitation-based budget (MR),
v) reconstruction-based budget (R)

The first scenario (i.e., NO) means that no MR&R actions are allowed to treat the network. The second scenario (i.e., PM) describes that the highways agency allocates the amount of money sufficient to maintain the entire road with preventive maintenance (equal to 700 Billion IDR per year). The third, fourth, and fifth scenarios mean that the budget is sufficient to treat the entire road with the light rehabilitation (i.e., LR), the medium rehabilitation (i.e., MR), and the reconstruction (i.e., R), respectively (see Table 3 for relevant budget sizes). Figure 6 shows the frequency distribution of IRI in the fifth year in the case of NO-scenario, where the IRI distribution tends to move to the right-side of graph relative to the starting year. This result is reasonable to expect, since the highways agency does not implement any MR&R, and thus the pavement condition deteriorates significantly by the fifth year.

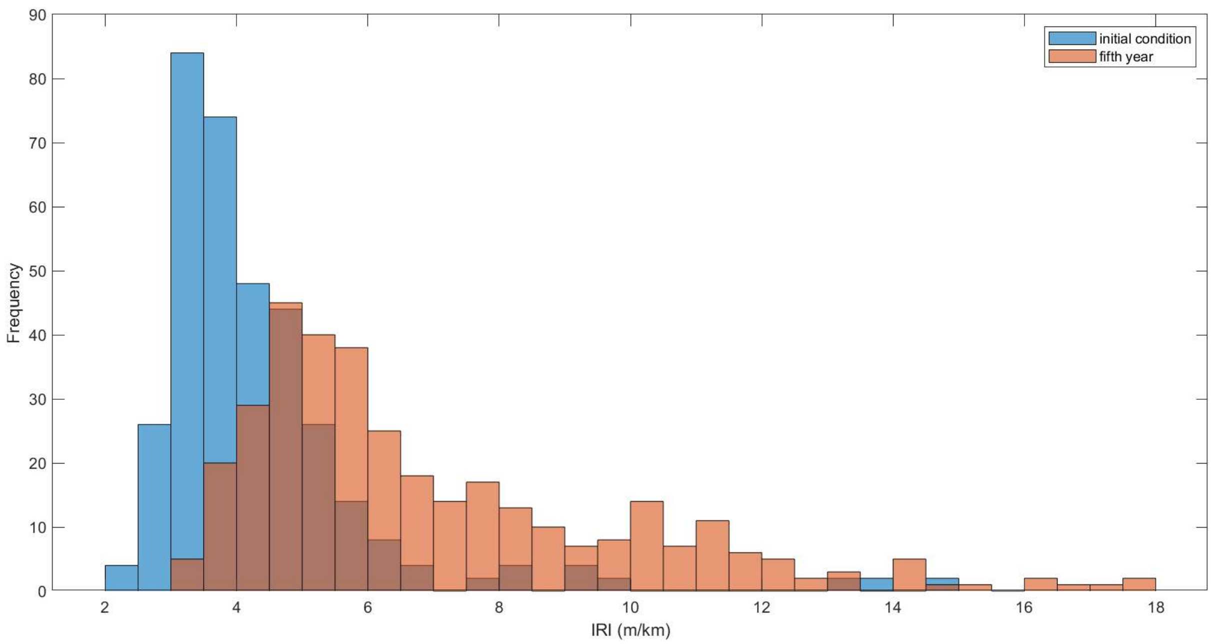


Figure 6: Distribution of IRI without any interventions

In the case that the agency has a budget allocation to maintain the roads, the MR&R action is then implemented by considering the condition of the pavement. However, because the threshold range influences the decision on MR&R, the appropriate value of the threshold is firstly checked. The setting of thresholds should balance the improvement of pavement condition and the efficiency of budget utilisation. For instance, the narrower range of threshold setting is helpful for improving the pavement condition sooner. However, it might only be possible to improve a small number of segments due to the budget constraint. Then, in some period, all pavements may be in a good condition but in some other period, many more pavement stretches may be worse off due to insufficient budget made available.

On the contrary, the wider range of thresholds might decrease the MR&R cost. But it will significantly degrade the pavement condition, resulting in an increase of the VOCs to the users. Thus, a question arises, what range of values for threshold should we use? The setting of a threshold is then evaluated by utilising the difference of total VOC. To obtain the difference parameter, the total VOC incurred *with* the MR&R program is subtracted from the total VOC incurred *without* the MR&R program, where the total VOC is the sum of VOC incurred on the RTN in 5 years. This difference value is able to capture the benefit that traffic users gain. In addition, it can be used to check the effectiveness of budget utilisation, where the ineffective budget spending due to the threshold setting will give a smaller value, as the MR&R is only implemented over a smaller part of RTN.

Variable π_1 is checked in the range of 2 – 6, π_2 in the range of 4 – 8, π_3 in the range of 6 – 10, π_4 in the range of 8 – 12, respectively. Furthermore, the constant weighting factor (i.e., *j*) is evaluated in the range of 1 – 3. From the numerical experiments, it was found that the parameters of π_1=2, π_2=4, π_3=6, π_4=8, and *j*=2 provide suitable results with various budget scenarios, which is depicted in Table 4. In addition, by comparing the results between *j*=1 and *j*=2, the benefit of incorporating the threshold-based strategy within the algorithm is illustrated. As reflected in Table 4, the model with MR&R threshold gives a higher VOC difference than the conventional one (i.e., without MR&R threshold). For instance, in the case of R-budget scenario, the model with MR&R threshold (*j*=2) is likely to save up to 13 billion IDR (=3695-3682) of VOC, compared to the model without MR&R threshold (*j*=1). A similar result was also found in the case of lower budget availability under MR- budget scenario, where the proposed heuristic can save VOC worth up to 5 billion IDR(=3447-3442). If the budget level is even lower such as the LR- budget scenario, the threshold strategy does not add more benefits. This result implies that the MR&R threshold performs well to guide the algorithm efficiently in deciding the MR&R action.

Table 4: Parameter setting of MR&R threshold and its weighting factor

Number	Budget scenario	Difference in total VOC *without* and *with* MR&R (billions of IDR)						
			j=2			*j*=3		
		j=1*	π_1=2; π_2=4; π_3=6; π_4=8;	π_1=2; π_2=4; π_3=6; π_4=12;	π_1=2; π_2=4; π_3=10; π_4=12;	π_1=2; π_2=4; π_3=6; π_4=8;	π_1=2; π_2=4; π_3=6; π_4=12;	π_1=2; π_2=4; π_3=10; π_4=12;
1	PM	998	998	998	998	998	998	998
2	LR	2,664	2,664	2,607	2,664	2,362	2,362	2,664
3	MR	3,442	3,447	3,391	3,441	3,275	3,275	3,432
4	R	3,682	3,695	3,591	3,666	3,379	3,379	3,572

* *infers* that the threshold strategy is not incorporated in the model.

Figure 7 illustrates the MR&R action outcomes with the budget scenario R. In the first year, the model estimates implementing the reconstruction over most of the RTN (i.e., 84.5% of segments) and implementing the medium rehabilitation in the rest of the RTN. However, in the second year, the reconstruction action is not recommended, and the model suggests implementing no action for the majority of the network (i.e., 86.6%), the light rehabilitation over a small part (i.e., 1.4%), and the medium rehabilitation over 12 % of the network. The number of light rehabilitation instances increases in the third year (14.6%), fourth-year (16.3%), and fifth-year (15.7%). This result describes the benefit for having a higher budget allocation in the earlier year than later. Although a higher spending occurs in the first year, in the years after, the number of MR&R interventions and the money spent will significantly decrease. The vehicle users also benefit from the higher spending of MR&R in the initial year. For instance, passenger car users enjoy the decrease in VOC by up to 8% from what was incurred in the first year.

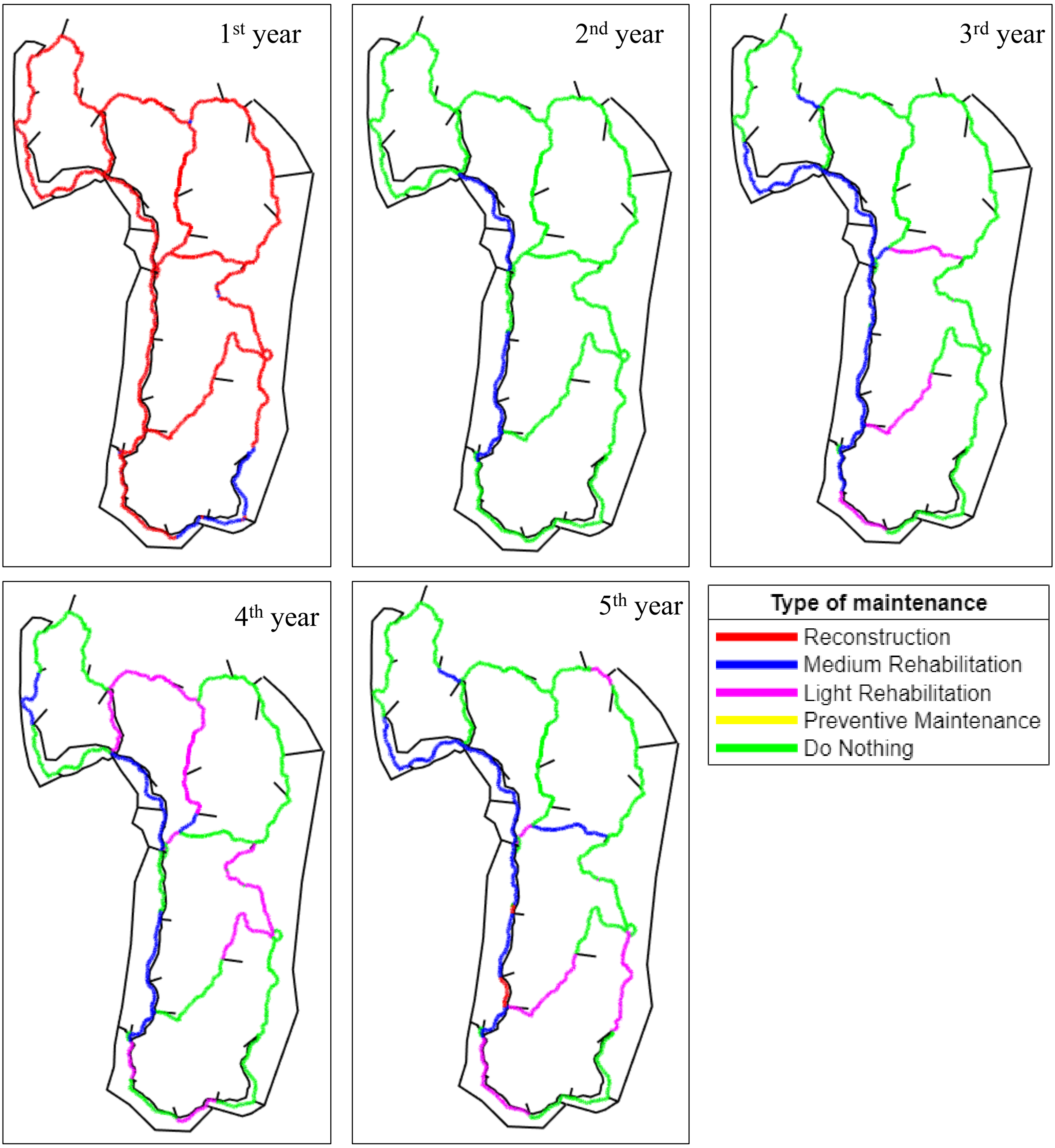


Figure 7: MR&R in the road network based on reconstruction-based budget scenario

Table 5 compares the average IRI in various budget scenarios within the time horizon. Since the R scenario spends the highest amount of money on MR&R, it then provides the lowest IRI. The LR, MR, and R scenarios illustrate a similar pattern in terms of correlation between the average IRI and the budget size, in which a higher budget provides a better IRI. In addition, in all scenarios (except NO), the model provides optimal solutions that require the MR&R spend less than the budget allocation. It is also interesting to point out that the R scenario spend is only slightly more than the MR scenario. The R scenario spend is the highest in the first year (i.e., 96.01% of budget allocation) and in rest of the years, the R scenario spends no more than 21.79 % of budget allocation. This outcome is derived by the fact that the highest spending in the first year successfully restores the performance of pavement, and then, in the remaining years, the agency only needs to maintain the performance with smaller sums of money.

Table 5: Average IRI based on the budget scenarios

Budget scenarios	Total budget allocated in five years (Billion IDR)	Total spend in five years (Billion IDR)	Average IRI (m/km)					
			1st year	2nd year	3rd year	4th year	5th year	Over 5 years
NO	-	-	4.94	5.58	6.25	6.96	7.71	6.29
PM	3,501.91	3,501.56	4.61	4.98	5.23	5.74	5.94	5.30
LR	17,509.53	17,509.10	4.05	3.85	3.84	3.53	3.18	3.69
MR	38,520.97	27,528.09	3.38	2.60	1.69	1.76	1.80	2.25
R	91,049.57	28,287.74	1.50	1.82	1.80	1.84	1.75	1.74

4.2 MR&R program with MTN development

This section analyses the influence of MTN development on the MR&R program, specifically, by pointing out the development of the railway and seaway links. The railway is newly developed in Sulawesi with an average speed of 80 km/hour, while the seaway developed has an average speed of 50 km/hour. The seaway involves operating a new route near the coastal area (i.e., short sea liner) by utilising the current seaports with Ro-Ro vessels. Each vessel can carry up to 62 trucks, and hence the capacity of the Ro-Ro vessel is set as equal to 1000 tonnes per trip. The unloading capacity is set to 400 tonnes and 700 tonnes per hour for railway and seaway, respectively. The transport charges for goods are set equal to 15,000 IDR, 16,000 IDR, and 10,000 IDR per tonne per km by trucks, railways, and seaways, respectively. Using the trucks does not involve any loading-unloading charges, but, the railway and seaway users incur additional loading-unloading costs. In the case of passenger users, the travel fare and mode capacity are set as presented in Table 6.

Table 6: The parameters related to the MTN

No	Items	Unit	Roadway	Railway	Seaway
1	Travel speed	km per hour	30	80	50
2	Practical load	tonnes per mode	16	500	1,000
3	(Un)loading capacity at terminal	tonnes per hour	-	400	700
4	Freight travel cost	IDR per tonnes per km	15,000	16,000	10,000
5	(Un)loading cost at terminal	IDR per tonne	-	5,000	2,500
6	Passenger travel fare	IDR per person per km	-	2,000	500
7	Passenger mode capacity	persons per mode	2	560	200

The MTN development in this article is then divided into 3 cases, viz. the development of railway (RD), the development of seaway (SD), and the development of both seaway and railway (MTND). Figure 8 depicts the freight flow in the cases *with* and *without* the MTN development. Due to the development of MTN, some of the traffic flow on the road is shifted to the railway and seaway. This is indicated by the decrease of vehicle kilometres of travel (VKT) by trucks up to 20%. This shift can be illustrated by the freight flow changes in the network (see Figure 8). Notice that with the presence of MTN on the eastern side of the network (see black rectangle), the freight flow on the road network reduces from >28,000 tonnes/hour (red colour) to 21,000 – 28,000 tonnes/hour (pink colour). This change is strongly driven by the existence of seaway and/or railway at those sides. In the middle of the network (see black circle) the freight flow by road has not changed because there is no MTN development at that location.

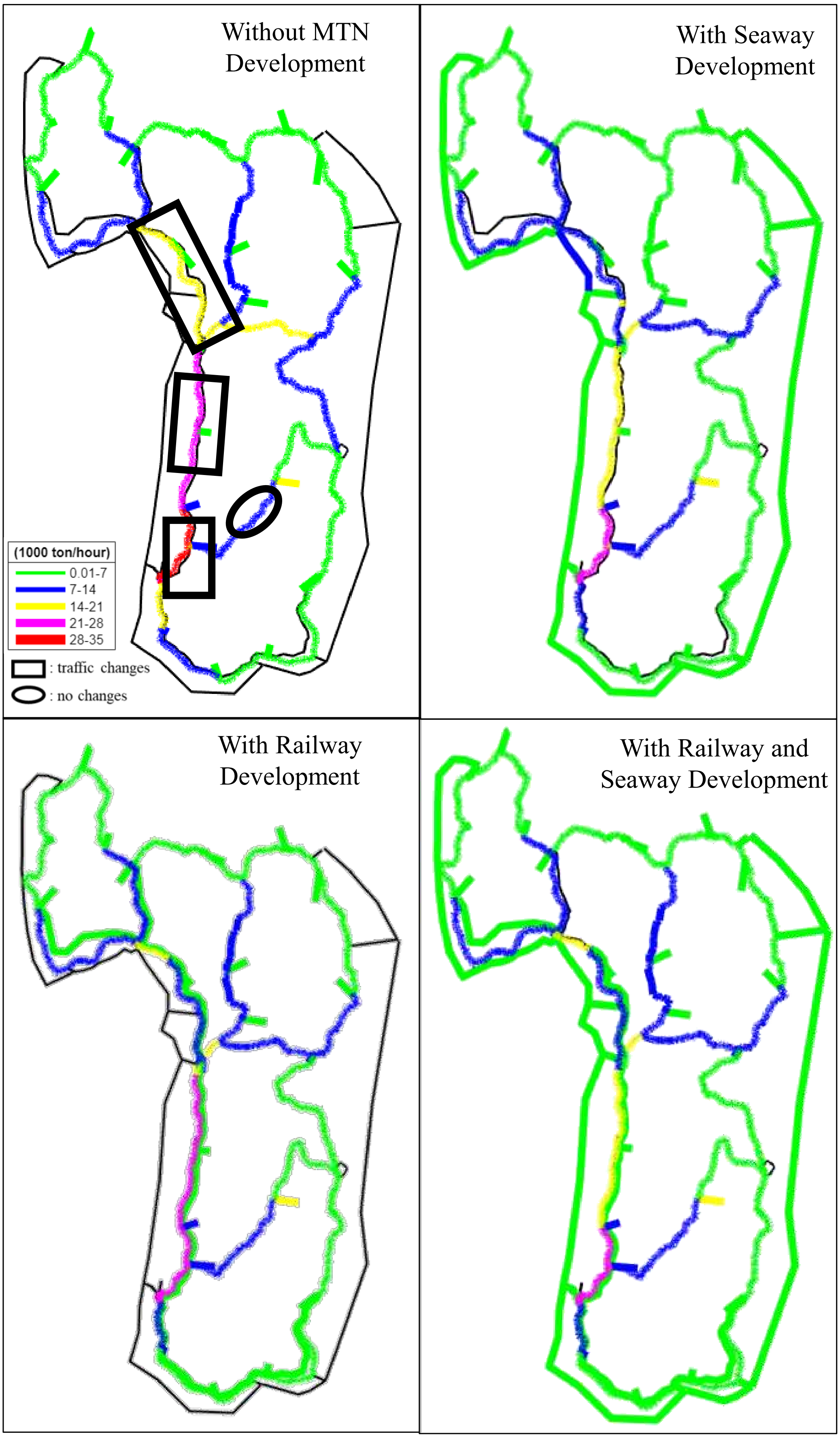


Figure 8: Freight flow *without* and *with* MTN development

The shifting of freight flow also impacts the pavement condition, as can be seen in Figure 9 which compares the distribution of IRI with the NO budget scenario. The IRI distribution with MTND, RD and SD developments in the fifth year has moved to the left of the graph line without any development, though the mean of IRI seems relatively similar for all development cases. This means that all development scenarios produce a better IRI distribution compared to the without scenario. However, the MTND possesses the highest peak, which implies that it can generate a better pavement condition even without any MR&R program. The development of railway and seaway simultaneously will increase the shifting of traffic away from road network causing slower pavement deterioration.

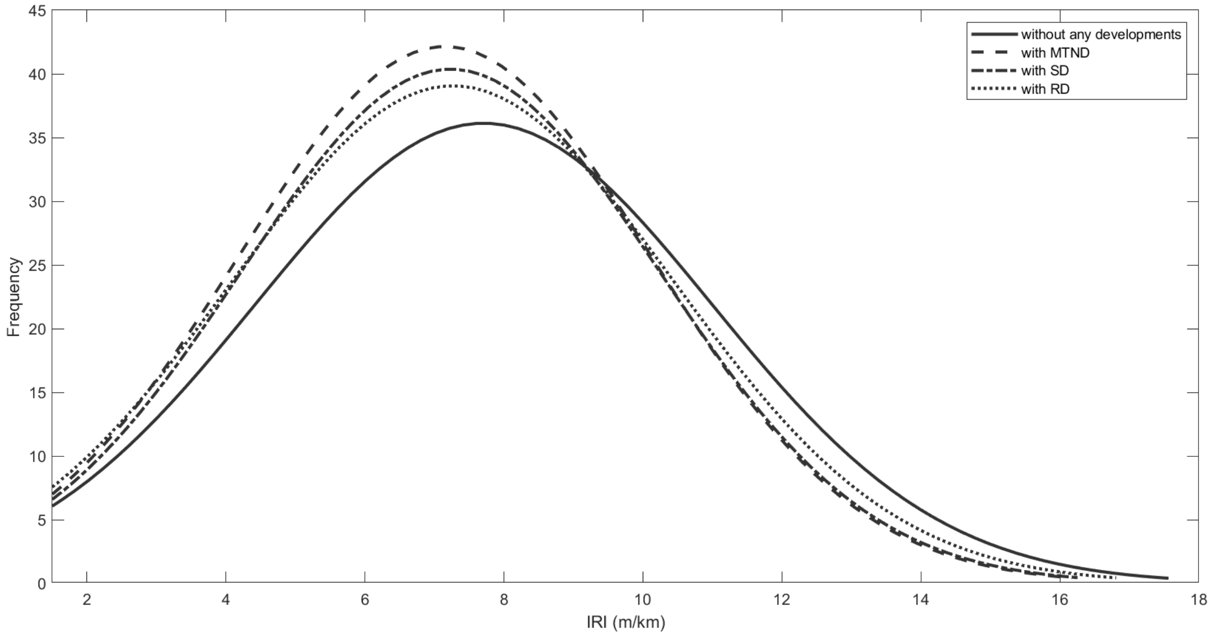


Figure 9: IRI distribution in the NO-budget scenario with and without the development of MTN in the fifth year

In case that the budget is made available for implementing MR&R program, the development of MTN, not only improves the performance of IRI but also decreases the total expenditure on the MR&R program. Figure 10 shows that the MTN performs better even with a smaller budget. In the case of a higher budget, the MTN can provide comparable performance with a smaller MR&R cost. Comparing the annual budget allocation to MR&R costs for five years, the simulation results show that the annual budget allocation of less than 6,000 billion IDR is fully utilised for implementing the MR&R (see the linear part of the red line), and any allocation of more than that sum is only partially used. Furthermore, an annual budget higher than 6,000 billion IDR does not give a significant improvement to the IRI, hence, the budget allocation should be set around this value to provide an optimal MR&R program.

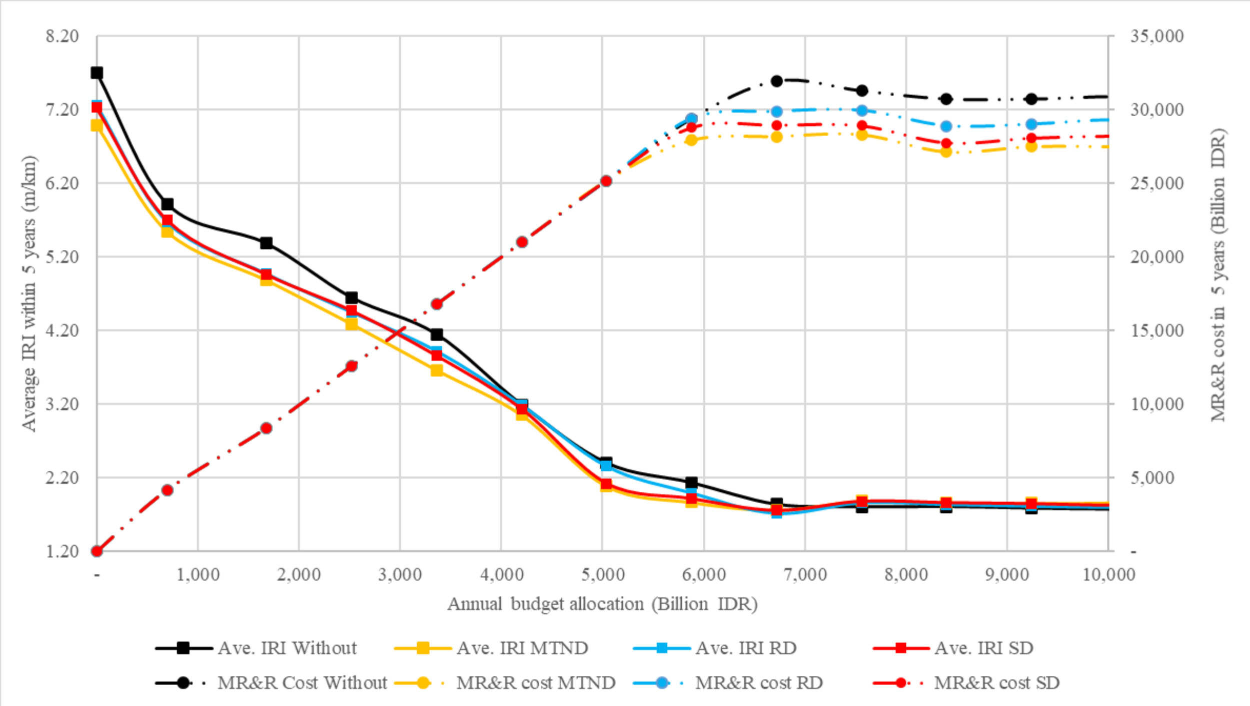


Figure 10: Average IRI and total MR&R cost in five years with various annual budget

The integration proposed in this article gives an opportunity for investigating the impact of the development of MTN from two different perspectives, namely the users and the highways agency. The users can enjoy better performance from improved traffic conditions (i.e., reduced vehicle hours of travel -VHT and VKT) and the IRI condition that influences the users' VOCs, and the highways agency benefits from better pavement conditions thus lower spending. Table 7 shows the network performance in the case of MTN development, where all MTN developments provide a better traffic performance based on the VHT and the VKT. Those parameters are practically used for investigating the advantages of MTN development. Table 7 also describes that development of seaways attract more freight users than the railways would. This result may be caused by the fact that the Ro-Ro offers a cheaper alternative with better transhipment process. On the other hand, passenger users prefer railways more than the seaway. However, it is noted that these shares only captured the intercity travel without any consideration to the last-mile travel. Hence, they might be seen as on the higher side than if the last-mile travel were included. Overall, the developments bring a positive impact to the users as they experience a lower VOC in TN.

The highways agency also benefits from the slower deterioration of pavements due to the development of MTN even in the case of no budget available. If they have a budget made available for the MR&R program, they can potentially reduce the total spending on roads delivering higher value for money spent. The benefits captured from both perspectives within the model in this article offer valuable insights thus supporting the case for MTN development compared to many other studies that remain solely focused on a user perspective.

Table 7: Network performance without and with the development of MTN

No	Parameters	Units	Without any development	MTND	RD	SD
1	Vehicle hours of travel by freight user	million vehicles hours	0.39	0.21	0.24	0.27
2	Vehicle kilometres of travel by freight user	million vehicles km	1.08	0.81	0.94	0.84
3	Roadway shares for freight user*)	%	100	83.1	94.1	85.8
4	Seaway shares for freight user*)	%	-	12.7	-	14.2
5	Railway shares for freight user*)	%	-	4.2	5.9	-
6	Roadway shares for passenger user**)	%	100	41.3	51.7	58.2
7	Seaway shares for passenger user**)	%	-	23.7	-	41.8
8	Railway shares for passenger user**)	%	-	34.9	48.3	-
9	Total VOC for cars in 5 years with NO budget	trillion IDR	34.38	13.36	14.75	22.05
10	Total VOC trucks in 5 years with NO budget	trillion IDR	16.86	12.34	14.38	13.51
11	Average IRI in five years with NO budget	m per km	6.29	5.97	6.03	6.01
12	MR&R cost with R budget	trillion IDR	28.29	25.18	27.11	25.18

*) The mode shares are calculated based on tonne-km

**) The mode shares are calculated based on passenger-km

4.3 MR&R program considering the overloaded heavy vehicles

To investigate the application of the proposed model further, the model is utilised for describing the impact of OHV on pavement maintenance by considering the MTN development. Several studies were conducted on OHVs earlier (Pais *et al.*, 2019; Roeun and Mony, 2012; Sadeghi and Fathall, 2007), however, little evidence is available on how the OHVs affect the MR&R program with a consideration of MTN. In this numerical example, the practical loading of trucks is higher than the allowable load (i.e., 16 tonnes), where each truck carries up to 24 tonnes. Table 8 describes the impact of OHVs on pavement condition and traffic performance. Since each truck carries more goods, the OHV can reduce the kilometres of travel of all vehicles by up to 33%, which can be regarded as a positive impact on the traffic performance. However, the existence of OHV severely affects the pavement condition, in which the average IRI can increase by up to 1.46 times in the NO-budget scenario. A similar pattern appears when the MTND is considered, but the average IRI is 5.1 % lower than without the MTND. The deterioration in pavement condition due to the overloading linearly increased the budget spent when applying the MR&R program. The cost escalates almost twice the cost of without the overloading practice. But the MTND could minimise the cost escalation. For instance, in the R scenario, for achieving a similar pavement condition, the MR&R expenditure estimated in the case of MTND is 9.6% lower than that without the MTND. This result may also explain why the OHV is challenging to handle without a strong regulation. From the perspective of the owner of the goods, the OHV can decrease the transportation cost, thus maintaining the lower product price. However, from the perspective of truck owners and the highways agency, it significantly increases their cost of operating the vehicle and maintaining the roads respectively. The development of MTN generally can release such pressure, where the MR&R cost can somewhat decrease. The slower deterioration of pavement, which affects MTND, also influences lowering the VOC of trucks.

Table 8: Pavement condition and MR&R cost with OHV practice

Parameter	Unit	Without any development		MTND	
		without OHV	with OHV	without OHV	with OHV
VKT of freight user	million km. vehicles	1.08	0.72	0.84	0.54
Average IRI with NO Budget	m per km	6.29	9.22	5.97	8.20
MR&R cost with R Budget	trillion IDR	28.29	53.86	25.18	48.66

5. Concluding remarks

This article presents an integrated model of MR&R of roads embedded with multiclass traffic assignment. The model is constructed within the framework of optimisation that aims to enhance the network-level pavement condition by deciding a suitable MR&R course of actions. The shifting of flow away from roads due to MTN development is successfully captured by the multimodal traffic assignment, which is then utilised as input to the MR&R model. To handle the optimisation problem, the greedy heuristic algorithm is modified by including a threshold-based strategy factor. The numerical example with an actual TN reveals that the development of MTN improves the traffic performance (i.e., VKT, VHT) and can reduce the MR&R cost. The model is also employed to analyse the impact of OHVs in practice, which presents a contradicting perspective of users and the highways agencies. The OHV can reduce the VKT benefitting the owner of the goods, but it can increase the MR&R cost, which highways agencies wish to avoid. Both perspectives were captured effectively within the model, and it is shown that MTN development can minimise the impact of OHV practice from both perspectives.

The main conclusions from this paper are summarised as below:

- The proposed model allows simultaneously evaluating the impact of MTN development along with the MR&R program. In contrast with the studies that remain focused on the impact of MTN development from a traffic user perspective, the integrated model in this article allows for analysing the advantages of MTN development from the highway agency perspective, in addition to accounting for the traffic user response. This model, thus, offers a comprehensive understanding of the development of MTN.

- The proposed greedy heuristics that combine the threshold-based strategy with an optimisation modelling framework, efficiently guides the algorithm to program the MR&R. The proposed method provides the MR&R program which not only minimises the IRI but also reduces the VOC to users. In addition, the thresholds that were previously adjusted based on the experience, can now be optimally determined within the proposed method.
- The numerical experiments with a large real-life network show that the development of seaway and railway simultaneously improves the network performance substantially. However, in the case that simultaneous development is not possible, developing seaways alone might attract more freight users than the railways would. The seaway development potentially reduces not only the freight user costs (i.e., truck VOCs) up to 30%, but also the agency costs (i.e., MR&R cost) by up to 10.68% saving substantial sums of money to the economy. The development of MTN also brings a positive benefit for the highway agency even with OHVs in practice that are hard to contain in some countries.

The future works may consider incorporating the network design problem for developing the MTN. The problem could then help to decide the optimal capacity of MTN development required and its travel fare by considering the impact on the maintenance program of roadways, seaways and railways. Therefore, the problem can comprehensively capture the impact of MTN decisions on the pavement maintenance program and other modes. The current model excludes the cost of developing/maintaining railway lines and sea links. These costs could be internalised allowing for evaluating the strategic advantage of developing MTN. The future work can thus extend the advantages of the integrated modelling for selecting optimal decisions involving MTN development presented in this article. The performance of proposed greedy heuristics can also be assessed further by solving the optimisation problem by other solution techniques. For instance, the performance of greedy heuristics can be compared to the metaheuristic-based approaches (e.g., Particle Swarm Optimization, Genetic Algorithm, Simulated Annealing) by highlighting the solution quality and the computation effort required to solve real-life problems.

Acknowledgements

The work was partly supported by the LPPM ITB (PN-2019).

Data Availability Statement

Data not available due to [ethical/legal/commercial] restrictions

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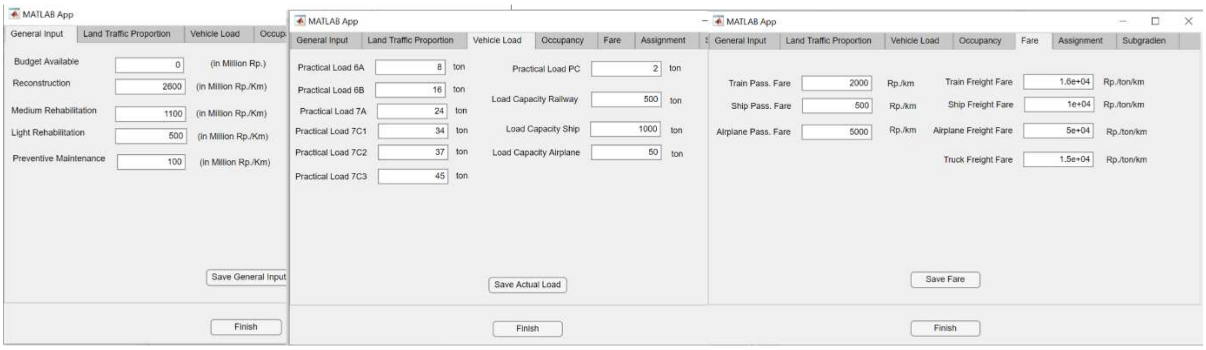
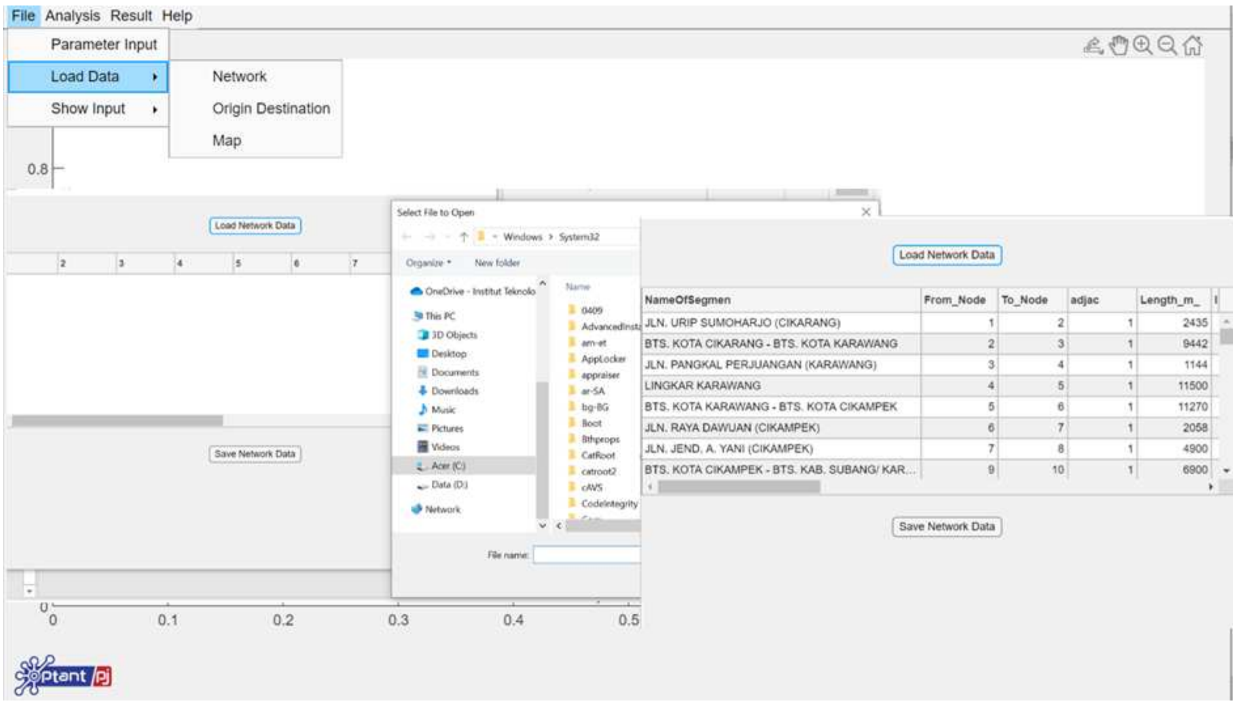
Appendix: OPTANT PJ

OPTANT PJ is an acronym (in Bahasa) for "***opt**imasi jaring**an** **t**ransportasi untuk **p**emeliharaan **j**alan*", which is initially developed by integrating the MR&R model with the traffic assignment. The traffic assignment in the earlier version of OPTANT PJ only considers the road network. We update the software by including the multimodal transportation network with multiclass user equilibrium. The general step for implementing using OPTANT PJ is described as follows:

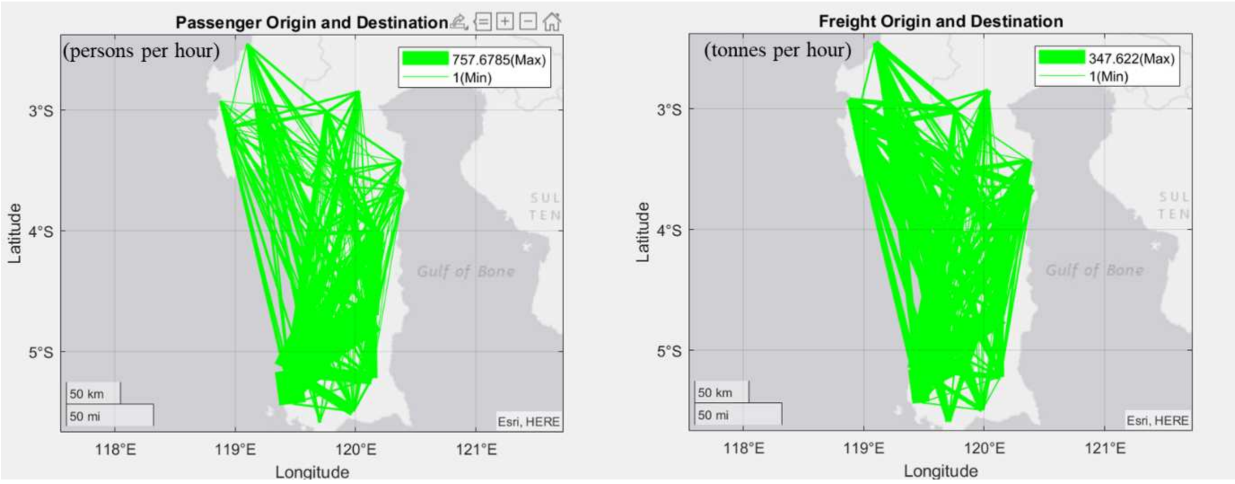
Step 1: Input the parameter for the MR&R model and the Multimodal Traffic Assignment.



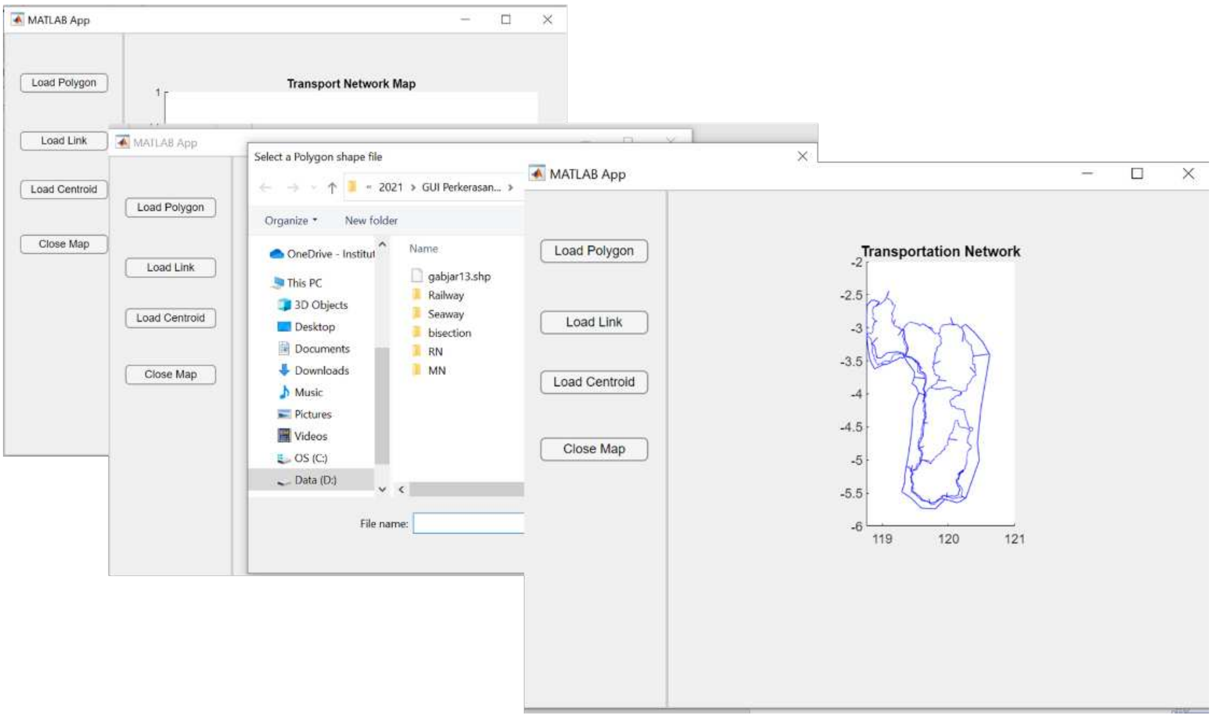
Step 2: Input the data of transportation network and origin-destination.



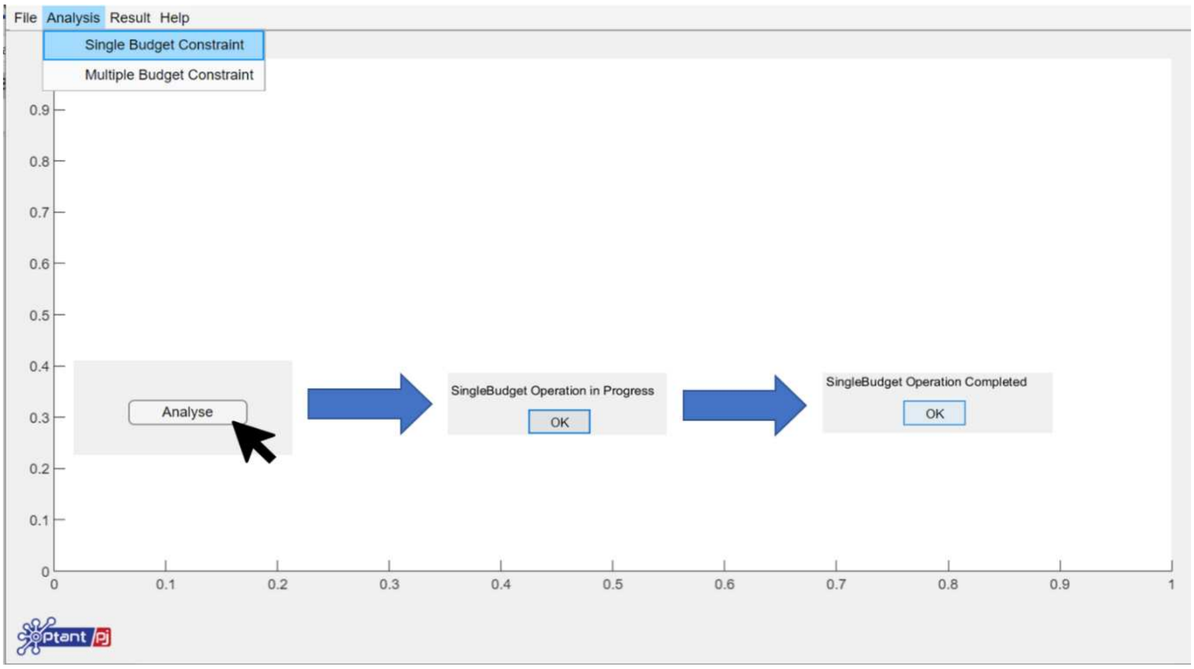
Step 3: Visualise the Origin-Destination data.



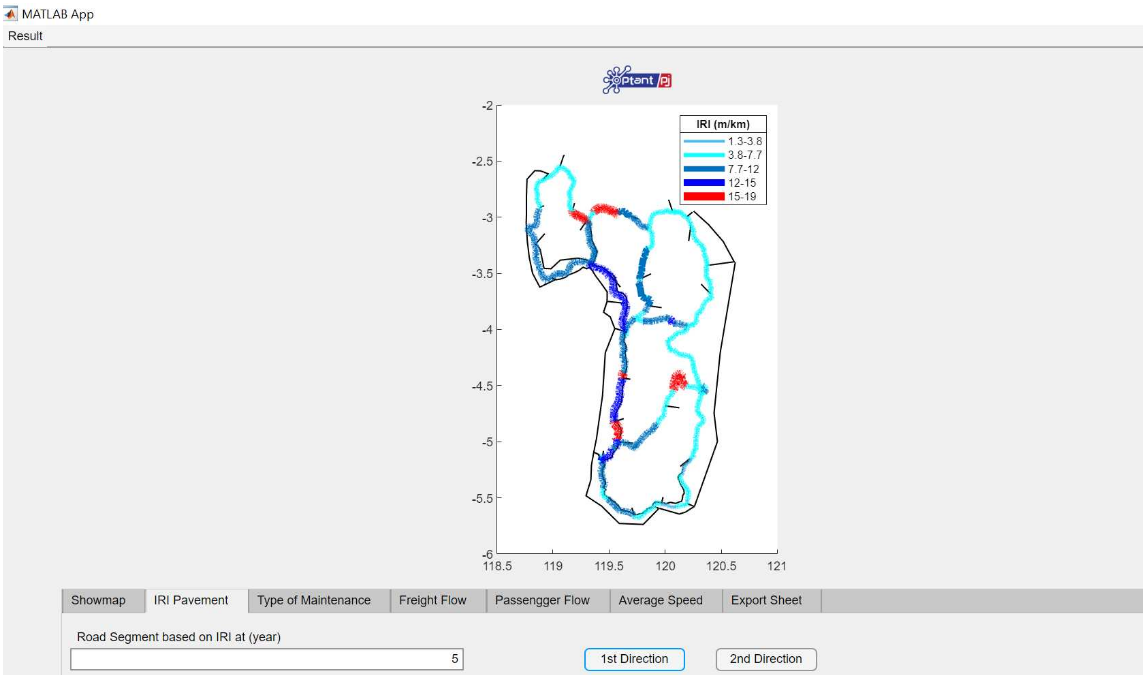
Step 4: Input the GIS data for map.



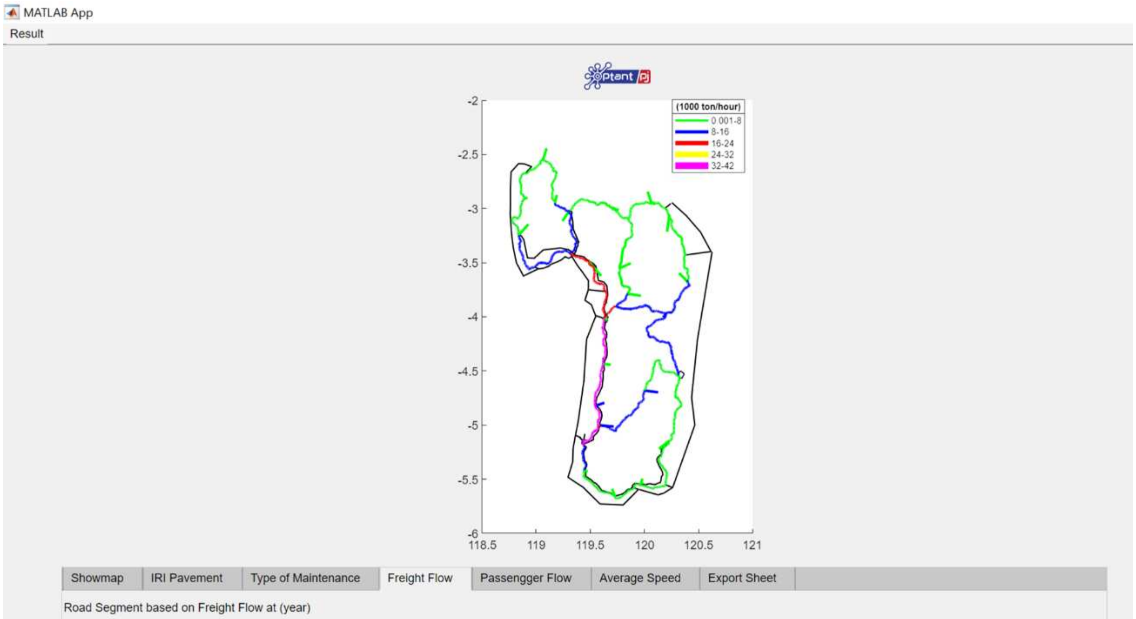
Step 5: Run the MR&R model with the multimodal traffic assignment.



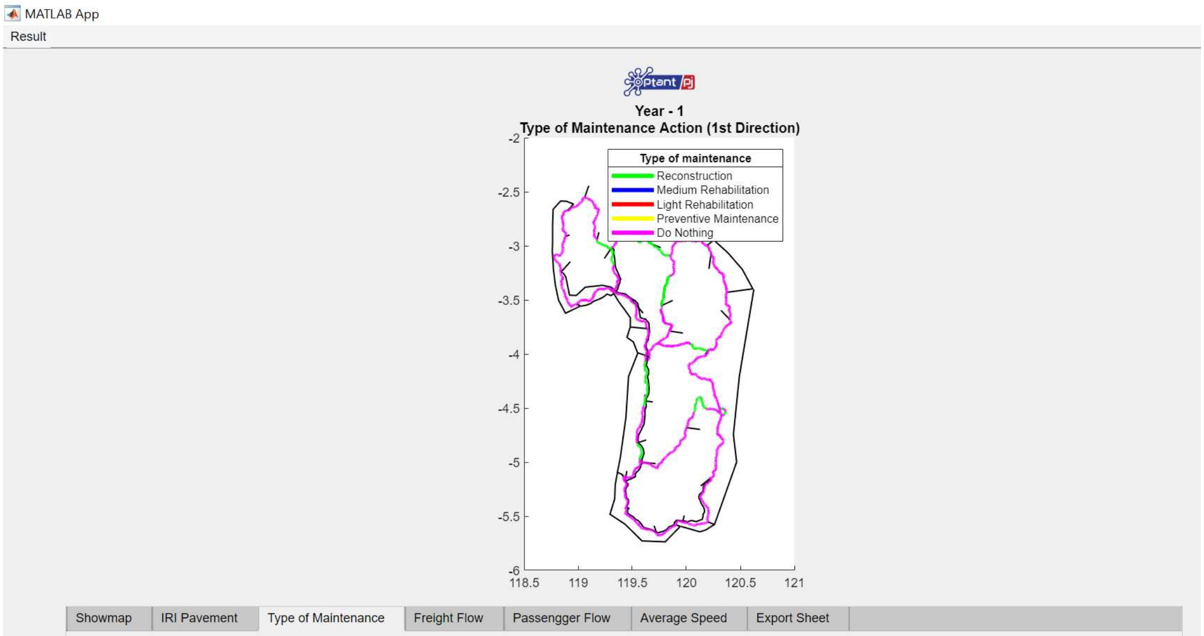
Step 6: Collect the figure output of IRI



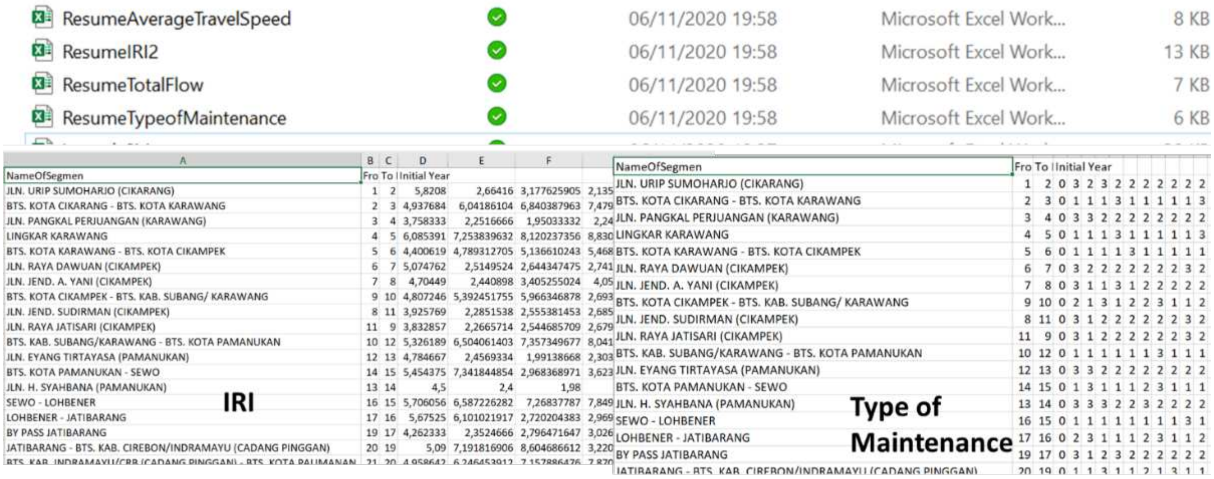
Step 7: Collect the figure output of Freight Flow



Step 8: Collect the figure output of Type of Maintenance



Step 9: Collect the numerical output by exporting into Ms. Excel



ResumeAverageTravelSpeed	06/11/2020 19:58	Microsoft Excel Work...	8 KB
ResumeIRI2	06/11/2020 19:58	Microsoft Excel Work...	13 KB
ResumeTotalFlow	06/11/2020 19:58	Microsoft Excel Work...	7 KB
ResumeTypeofMaintenance	06/11/2020 19:58	Microsoft Excel Work...	6 KB

IRI

A	B	C	D	E	F	
NameOfSegmen	Fro	To	Initial Year			
JLN. URIP SUMOHARJO (CIKARANG)	1	2	5,8208	2,66416	3,177625905	2,135
BTS. KOTA CIKARANG - BTS. KOTA KARAWANG	2	3	4,937684	6,04186104	6,840387963	7,479
JLN. PANGKAL PERJUANGAN (KARAWANG)	3	4	3,758333	2,2516666	1,95033332	2,24
LINGKAR KARAWANG	4	5	6,085391	7,253839632	8,120237356	8,830
BTS. KOTA KARAWANG - BTS. KOTA CIKAMPEK	5	6	4,400619	4,789312705	5,136610243	5,468
JLN. RAYA DAWUAN (CIKAMPEK)	6	7	5,074762	2,5149524	2,644347475	2,741
JLN. JEND. A. YANI (CIKAMPEK)	7	8	4,70449	2,440898	3,405255024	4,05
BTS. KOTA CIKAMPEK - BTS. KAB. SUBANG/ KARAWANG	9	10	4,807246	5,392451755	5,966346878	2,693
JLN. JEND. SUDIRMAN (CIKAMPEK)	8	11	3,925769	2,2851538	2,555381453	2,685
JLN. RAYA JATISARI (CIKAMPEK)	11	9	3,832857	2,2665714	2,544685709	2,679
BTS. KAB. SUBANG/KARAWANG - BTS. KOTA PAMANUKAN	10	12	5,326189	6,504061403	7,357349677	8,041
JLN. EYANG TIRTAYASA (PAMANUKAN)	12	13	4,784667	2,4569334	1,99138668	2,303
BTS. KOTA PAMANUKAN - SEWO	14	15	5,454375	7,341844854	2,968368971	3,623
JLN. H. SYAHBANA (PAMANUKAN)	13	14	4,5	2,4	1,98	
SEWO - LOHBENER	16	15	5,706056	6,587226282	7,26837787	7,849
LOHBENER - JATIBARANG	17	16	5,67525	6,101021917	2,720204383	2,969
BY PASS JATIBARANG	19	17	4,262333	2,3524666	2,796471647	3,026
JATIBARANG - BTS. KAB. CIREBON/INDRAMAYU (CADANG PINGGAN)	20	19	5,09	7,191816906	8,604686612	3,220
BTS. KAB. INDRAMAYU/CBB (CADANG PINGGAN) - BTS. KOTA PALIMANAN	21	20	4,958642	6,246453912	7,157886476	7,870

Type of Maintenance

NameOfSegmen	Fro	To	Initial Year										
JLN. URIP SUMOHARJO (CIKARANG)	1	2	0	3	2	3	2	2	2	2	2	2	2
BTS. KOTA CIKARANG - BTS. KOTA KARAWANG	2	3	0	1	1	1	3	1	1	1	1	1	3
JLN. PANGKAL PERJUANGAN (KARAWANG)	3	4	0	3	3	2	2	2	2	2	2	2	2
LINGKAR KARAWANG	4	5	0	1	1	1	3	1	1	1	1	1	3
BTS. KOTA KARAWANG - BTS. KOTA CIKAMPEK	5	6	0	1	1	1	1	3	1	1	1	1	1
JLN. RAYA DAWUAN (CIKAMPEK)	6	7	0	3	2	2	2	2	2	2	2	3	2
JLN. JEND. A. YANI (CIKAMPEK)	7	8	0	3	1	1	3	1	2	2	2	2	2
BTS. KOTA CIKAMPEK - BTS. KAB. SUBANG/ KARAWANG	9	10	0	2	1	3	1	2	2	3	1	1	2
JLN. JEND. SUDIRMAN (CIKAMPEK)	8	11	0	3	1	2	2	2	2	2	2	3	2
JLN. RAYA JATISARI (CIKAMPEK)	11	9	0	3	1	2	2	2	2	2	2	3	2
BTS. KAB. SUBANG/KARAWANG - BTS. KOTA PAMANUKAN	10	12	0	1	1	1	1	1	1	3	1	1	1
JLN. EYANG TIRTAYASA (PAMANUKAN)	12	13	0	3	3	2	2	2	2	2	2	2	2
BTS. KOTA PAMANUKAN - SEWO	14	15	0	1	3	1	1	1	2	3	1	1	1
JLN. H. SYAHBANA (PAMANUKAN)	13	14	0	3	3	3	2	2	3	2	2	2	2
SEWO - LOHBENER	16	15	0	1	1	1	1	1	1	1	1	3	1
LOHBENER - JATIBARANG	17	16	0	2	3	1	1	1	2	3	1	1	2
BY PASS JATIBARANG	19	17	0	3	1	2	3	2	2	2	2	2	2
JATIBARANG - BTS. KAB. CIREBON/INDRAMAYU (CADANG PINGGAN)	20	19	0	1	1	3	1	1	2	1	3	1	1