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Development of a Cross-Asset Model for the Maintenance of Road and Water Pipe Assets using AHP Method

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Abstract

Roads and water pipe assets undergo various deterioration processes due to the high demand for their services. Maintenance of these assets is often planned as individual assets, and the interdependency among different assets is neglected. An integrated framework for cross-asset maintenance is required for optimum utilization of the available funds for asset maintenance. To date, there are very few studies focusing on the use of the analytical hierarchy process (AHP) for cross-asset maintenance of roads and water pipe assets. Therefore, this research aims to develop an integrated fund allocation model for the maintenance of road and water pipe assets. A model was developed using AHP analysis based on expert opinions captured through a questionnaire in order to obtain optimum maintenance fund allocation for the cross-assets, roads, and water pipes. Then, a case study corridor segment with the considered cross-assets was selected, and a trade-off analysis was conducted for the intervention alternatives considering different levels of service (LOS) of the asset elements. The results of the trade-off analysis can be used to identify the optimum intervention alternative that satisfies the budget requirement and results in the maximum benefit. Overall, asset managers can use the approach presented in the present study to develop a cross-asset fund allocation model when multiple assets are involved in maintenance.

Keywords: Analytic Hierarchy Process (AHP); Road Assets; Water Pipe Assets; Cross-asset Maintenance; Fund Optimization; Trade-off.

1. Introduction

Infrastructure assets, including roads, bridges, and water pipes, are essential foundations for a nation. Infrastructure asset management is an integrated and multidisciplinary set of strategies for sustaining these public infrastructure assets. The performance of a public transportation system could not be evaluated merely based on a single asset type (i.e., on pavement or bridges alone) and needs to be evaluated for the system as a whole (cross-assets) since the maintenance of one asset will trigger the degradation of another asset. As a result, cross-asset management of the infrastructure is an important element in asset management. Pavement, bridges, tunnels, traffic equipment, congestion, public transportation, and various other types of individual management systems have emerged during the last decades. The pavement management system is the oldest and most abundant of these engineering management systems, and this is because pavements constitute almost 60% of the total infrastructure assets managed by transportation agencies [1].

The most common utility assets related to the roads include water distribution pipes, drainage pipes, and sewer pipes. The asset systems comprising roads and water pipes have a strong interdependency, as the maintenance of one asset can

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always enhance the deterioration of the other asset. These individual asset maintenance activities on the asset system create an extra cost for the management authorities by enhancing the need for frequent maintenance of the asset system. This often creates disruptions in the functionality of both asset groups. Therefore, integrated cross-asset maintenance strategies are required to overcome these issues. The major challenge in developing such a framework for cross-asset systems consisting of road and water pipe assets is the unavailability of a set of reliable relative weights derived considering multiple criteria for the maintenance of these assets. This is mainly because the maintenance planning of roads and water pipes is usually performed by two independent authorities, and the budgets are allocated separately. When multiple assets are considered together for maintenance, a proper methodology should be adopted to ensure all assets are fairly treated in cross-asset management. To apply the cross-asset optimization theories to an asset system, first, the individual asset systems need to be integrated into a single platform.

A single index showing the importance of the project is required to determine the weight of multiple assets within a project. This 'project index' helps prioritize all the multiple-asset projects being considered [2]. Such a sustainable cross-asset management framework consists of four steps: resource allocation, treatment selection, performance prediction, and overall performance evaluation [3]. Figure 1 shows a typical cross-asset management framework related to road assets.

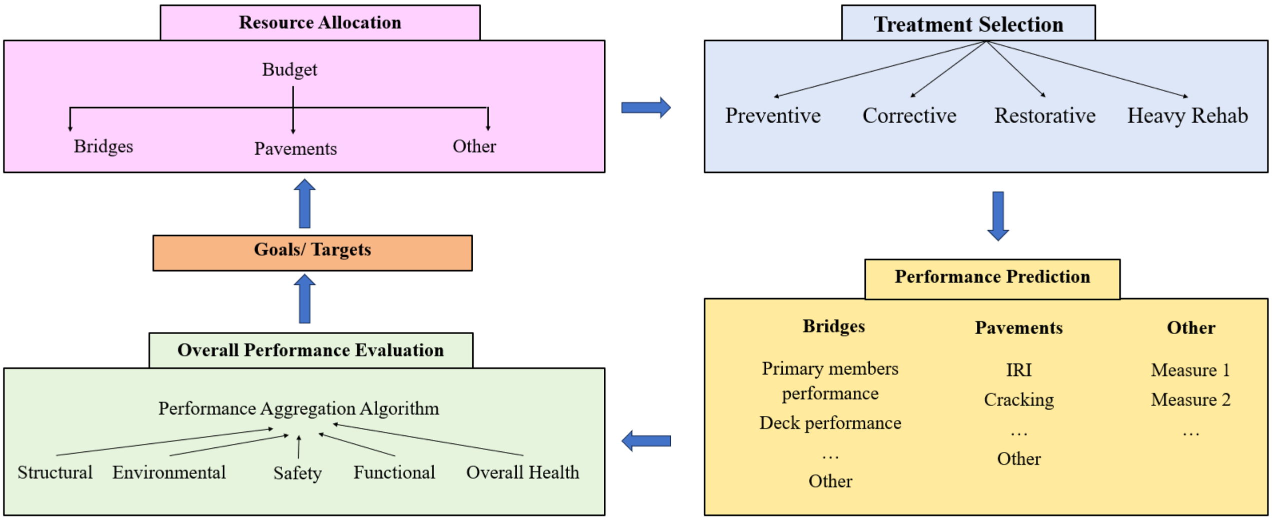

Figure 1. Cross-asset management framework adopted from Dehghani et al. [3]

According to Deix et al. [4], cross-asset management comprises high-quality information on asset inventory, the condition of such assets, management strategies, customer perceptions, and a definition of strategic targets. The top-down approach and bottom-up approach are the two methods used for cross-asset optimization [4–6]. In the bottom-up approach, resource allocation is influenced by the technical assessment of individual groups of assets at the object level, whereas resource allocation in the top-down approach is based on a central decision that deals with infrastructure at the network level. A comprehensive understanding of the overall state of the network is required for the top-down approach [4, 7]. Four main strategies are used for the cross-asset maintenance treatment [4]: (i) strategies based on a real combination of single asset-specific maintenance treatment; (ii) strategies based on a sequence of single uncombined maintenance treatments of single assets; (iii) an extension of the application area to combine asset-specific maintenance treatments; and (iv) a combination of the previous cross-asset treatment strategies.

Fund allocation decisions for assets should be made considering multiple criteria, and researchers have proposed different approaches, including the weighted sum method, goal programming, compromise programming, ε-constraint method, multi-attribute utility theory, analytic hierarchy process, and genetic algorithms. The weighted sum method is a simple approach compared to other methods. In this method, various objective functions are combined using positive weights to obtain the Pareto optimal set. The main drawbacks of this method are having different weight combinations that can generate the Pareto optimal set and the unpredictability of the distribution of the Pareto optimal set with the variation of the weight [8, 9]. Goal programming minimizes the weighted sum of deviations of all objective functions from their respective goals [8, 10]. Goal programming can be performed either as non-pre-emptive (when all objectives have comparable importance) or pre-emptive (when a certain objective is highly deviated and has a high weight) [2]. In compromise programming, the closest solutions to the ideal solution are identified by some measures of distance, such as the normalized deviation from the ideal solution measured by the family of metrics. This results in a reduction in the Pareto optimal set, making the analysis less complex [9].

The ε-Constraint method is another approach used for optimization by prioritizing one objective function while treating other objectives as constraints. Although this reduces convexity in methods like weighted sum, it is essential to identify the most suitable constraints to ensure Pareto optimality [8, 11]. Genetic algorithms are based on a population of solutions, and the natural selection for solving complex combinations for optimization is used to generate new solutions by using different methods such as reproduction, crossover, and mutation. This approach can be used to generate good solutions to complex combinatorial problems, although it requires high computational costs and programming complexity [9]. Multi-attribute utility theory and analytical hierarchy process (AHP) can be used to analyze and quantify multiple alternatives based on the preference of the decision maker. In the multi-attribute utility theory approach, it is difficult to construct the individual's utility function in a practical situation, and guidance from specialists in the field is often required [2, 10, 12].

Among all the available multi-criteria decision-making methods, the AHP is one of the most straightforward and widely adopted approaches [13–15]. AHP has been proven to be a multicriteria decision-making tool in different spheres and has found its applicability in supporting both subjective and objective-based choices in infrastructure projects with social impact [16]. The AHP focuses on modeling different problem structures that could achieve a hierarchical configuration through pair-wise comparisons [17]. According to Su and Hassan [18], AHP generally consists of the following five main steps: (i) structure a decision hierarchy defining the problem; (ii) select the acceptable options and criteria for assessing; (iii) determine the relative priorities of criteria and sub-criteria; (iv) determine the relative priorities of options; and (v) synthesize by calculating the overall priorities of options, sensitivity analysis, and making the decision. There is an overarching objective for every hierarchy from which the criteria and sub-criteria descend. A decision hierarchy can be structured by considering the three critical elements: the goal, acceptable options, and the relevant criteria for assessing the options, as shown in Figure 2. The goal is for the problem to be solved. The measures of performance used to judge the options for the goal are considered the criteria, where options are the alternatives available to achieve the goal. In the AHP method, the top-down approach of prioritization is used [18]. Accordingly, first, the criteria are prioritized. Subsequently, the sub-criteria (if available), options, and sub-options (if available) are prioritized in the same order.

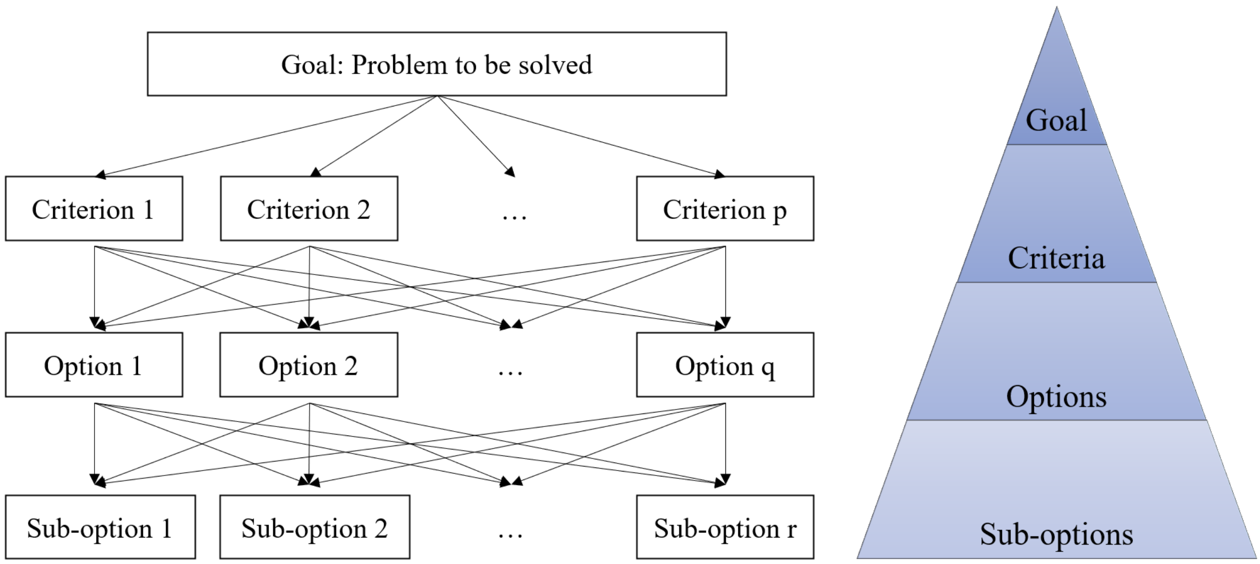

Figure 2. Structure of the AHP

There are some studies focusing on the use of the AHP method for the decision-making process for an individual asset (either a road asset or a water pipe asset), while there are a very limited number of studies focusing on the use of AHP for cross-asset maintenance combining more than one asset [19, 20]. Li et al. [21] used AHP in network-level infrastructure maintenance decision-making to determine the weighting of some preselected decision-making factors. The technique was explicitly applied to network-level pavement maintenance decision-making, considering five maintenance-related factors, such as pavement performance, pavement structure strength, traffic loads, pavement age, and road grade. All the results from the decision-making process were subsequently subjected to sensitivity analysis, and the most significant factors based on cost and service life were determined. Based on the weighting factors, the comprehensive ranking value was determined to indicate the maintenance priority of a road section in the network-level decision-making process. Rifat Hossain Bhuiyan et al. [22] used AHP to rank four maintenance projects on highways based on five criteria, such as annual average daily traffic (AADT), crash rate (crash per thousand vehicles), road corridor area, percentage of heavy vehicles, and percentage of non-motorized vehicles. The results revealed that crash rate has the highest criteria weight among the considered criteria, while AADT has the lowest criteria weight for the maintenance decision on the selected roads.

Van Hiep & Sodikov [23] proposed an approach using AHP to evaluate and rank the road network regions considering assets, cost, and traffic using data collected in Uzbekistan. The results from this study were used to identify the most important regions in the road network and the need for high priority to improve the road condition. In another study by Fawzy et al. [24], AHP was used to evaluate the criteria weights for the regular maintenance and rehabilitation of the roads in Egypt. They used six criteria, including pavement performance measured in terms of pavement quality index (PQI), road safety, traffic level, pavement age, road class, and construction quality, and these criteria were compared and weighted under feasibility and rationality. Based on the findings, PQI recorded the highest priority weights, exceeding 38% and 42% of the total weights for feasibility and rationality, respectively. Sharma et al. [25] used AHP to calculate different levels of service (LOS) for vehicles, pedestrians, and bicycles in an urban road infrastructure system, considering three criteria: the number of road users, safety, and neighborhood aesthetics. They found that the number of road users and safety have high impacts on all LOS, while neighborhood aesthetics has the lowest weight compared to the other two.

Orugbo et al. [26] developed a hybrid model using AHP and reliability-cantered maintenance (RCM) methods to evaluate road maintenance periodization. The study is based on a trunk road network of 3.387 km, and AHP was used to rank the maintenance priority of 15 sub-assets in the road infrastructure. The assessment was conducted using six criteria, such as function, downtime, utilization, maintenance requirements, regulation, and risk. The results showed that carriageways have the highest maintenance priority, while road markings and roadside telephones have the lowest maintenance priorities. Chaipetch et al. [27] used AHP to evaluate rural road maintenance prioritization using three criteria: economic factors, engineering factors, and social factors. The analysis was conducted considering four strategic systems (alternatives), such as logistic and integrated transport systems, tourism, reducing traffic congestion, and rural economic development. It was found that the economic factor is the most important factor among all the alternatives. Nautiyal and Sharma [28] developed a maintenance priority ranking for 203 low-volume rural roads in India using AHP, considering four critical criteria groups: pavement condition, traffic, utility value, and route type. The results revealed that the highest weight is allocated for pavement conditions measured using the pavement condition rating (PCR) value, while the lowest weight is allocated for the route type criterion.

Dalal et al. [29] used AHP to develop a condition index called ‘road score’ considering six criteria: road condition, traffic, backward population served, block non-development index (BNI) (socio-economic condition of the blocks), connectivity to services, and connection to the road network. Although AHP has been widely used in decision-making related to road infrastructure, the applications are mostly limited to the prioritization of road maintenance, the identification of high-priority regions of the network, the identification of asset elements for maintenance, and the comparison of maintenance options for roads. None of the studies reported in the literature have extended the AHP to optimize maintenance fund allocations for road infrastructure.

A number of studies have used AHP to prioritize different maintenance and rehabilitation aspects of water and wastewater pipe networks. Hassoun Nedjar et al. [30] used AHP to rank three criteria (physical, operational, and environmental) to make rehabilitation decisions on the drinking water network in the North-East area of Algeria. Based on the outcome of the AHP analysis, physical, operational, and environmental criteria recorded 35.4%, 55.6%, and 9% priority weights, respectively. In addition, an urgency level rating was used in this study to prioritize the rehabilitation of the selected pipe network. Orasanin et al. [31] determined the weights of the criteria for renewal of water supply networks using AHP. Altogether, 13 criteria were compared in this study, and the results revealed that water quality, investment value, frequency of failures, and pipe flow velocity possessed higher weights compared to other criteria such as pipe age, length, diameter, number of connections, soil condition, population density, pipe pressure, and hydraulic condition of the pipe.

Mezhoud et al. [32] conducted a study to prioritize the defects of an urban sanitation network, and AHP was used to calculate criteria weights of defect impacts on structural quality, repair cost, and repair time. The study was conducted on a network of 74.6 km long pipes, considering several defects, including infiltration/exfiltration, reduction of the hydraulic capacity, sand, clogging, collapse, surface degradation, chemical attack, and root intrusion. The results revealed that chemical attack, surface degradation, and internal abrasion of the pipe are critical defects requiring immediate intervention as the performance is between 25% and 50%. Further collapse was identified as the major defect in all the pipes studied, having very low pipe performance ($0 \leq P < 25\%$).

Aşchilean et al. [33] studied the selection of technology for the rehabilitation of domestic water distribution networks using AHP. In this study, seven decision criteria, such as the diameter of the pipe, length of the pipe, period of time required for installation, lifespan ratio between the rehabilitated pipe and non-rehabilitated pipe, pressure losses, price, and installation conditions, were considered. It was found that pressure losses and price have the highest impact on the rehabilitation technology selection. Kilinç et al. [34] studied the technical performance of individual water pipes based on physical, environmental, operational, and sub-factors, and the analysis was conducted using AHP. According to the results, it was found that physical and operational factors are more dominant for pipe performance compared to environmental factors. In addition, the critical factors identified under the categories of physical, environmental, and operational factors were pipe age (58% of total factor weight), soil type (50% of total factor weight), and number of water interruptions or system pressure (48% of total factor weight for each), respectively. As per the existing literature, the applications of AHP in the water pipe asset group have mostly been limited to identifying the failure modes, prioritizing the high-risk segments in the network, and identifying critical criteria for rehabilitation and high performance in the water network. The optimization of the maintenance cost of water pipe assets based on the AHP methods is still lacking in the published literature.

In the current literature, integrated asset management decision models considering the interdependency between water and road networks are very limited [35]. A recent effort in this area was made by Abu Samra et al. [36], where the authors developed a multi-objective decision support tool for intervention planning for integrated road and water networks. The study was conducted by selecting a network of 20 road sections covering water pipes of different materials. The deterioration curves for the physical state of both road and water networks were developed based on the date of construction, physical attributes, and condition assessment information. According to the results, cost was the driving factor in road interventions, while water pipes were more reliability-driven. In fact, when planning the maintenance of road assets, the extra cost is minimized by undertaking cost-effective early-stage interventions. On the other hand, water pipes are required to be kept in service without water outages, even at high brake rates, making them more reliability-driven compared to cost.

Mazumder et al. [35] developed a risk-informed decision-support framework for integrated water and road infrastructure asset management. This study modeled the dependency of road networks on water infrastructure assets as a geospatial-dependent model and identified the consequences of failure at the system level. It was observed that, due to the failure of a single segment (one of the riskiest pipelines and dependent road links) in the critical part, the network efficiencies of the water distribution system and road network dropped by 7.5% and 9.6%, respectively. Shahata & Zayed [37] developed an integrated risk assessment framework for three municipal infrastructures: sewer assets, water assets, and road assets. Altogether, eighteen factors covering economic, environmental, operational, and social impacts were considered in developing an overall risk rating using a Delphi-based AHP. The results revealed that pipe/road size and accessibility factors had the highest impact on the integrated risk index, and this risk index could be used to prioritize corridor rehabilitation projects.

Amador-Jimenez & Mohammadi [38] compared different budgeting scenarios, including worst-first, silos, and trade-off optimization, for an integrated system of infrastructure assets (i.e., pavements, sanitary sewers, storm sewers, and water mains) using mathematical programming algorithms. The results revealed that the worst-first method is not recommended, and the most suitable approach among the silos or trade-off needs to be selected based on the asset-management objectives. Further, applying the trade-off method resulted in 8.83% more cost savings compared to the silo method. The trade-off analysis resulted in high benefits when allocating the highest priority to water mains and lower priority to pavements and storm pipes in the investments. To date, there are no studies combining road assets with water pipe assets using real industry opinions for integrated maintenance prioritization and budget optimization. Further, no integrated approach has been reported on the use of AHP for the evaluation of different maintenance alternatives for road assets and water pipes through a trade-off analysis. Hence, the goal of the current study is to develop a prioritization model using AHP based on the opinions of the asset managers that can be used for maintenance fund optimization on a cross-asset system consisting of road assets and water pipe assets.

2. Research Significance

The degradation and maintenance of road infrastructure assets, such as road pavements and water pipes, are typically interconnected and behave as a single cross-asset system. Very often, asset-management-related decisions are made considering them as individual asset items, neglecting the inter-dependency. Most of the published research studies on road and water pipe asset management are conducted individually for a single asset type (road or water pipe asset). Researchers [20–30] have used AHP for multi-criteria decision-making related to various aspects of road asset maintenance, including prioritizing maintenance options, identifying high-priority regions, identifying critical road asset elements, and comparing maintenance options. Similarly, AHP has been used to make maintenance-related decisions about water pipe assets, including identification of failure modes, prioritizing high-risk network segments, and identifying critical criteria for rehabilitation and high performance in the network [31–35].

In addition, to date, there are very limited studies [36–39] focusing on the cross-asset maintenance approaches for roads and water pipe assets using AHP, and they used AHP to evaluate the risk of the integrated asset systems and for budgeting purposes. However, to date, there are no studies focusing on the use of AHP to optimize the maintenance fund allocation for road assets or water pipe assets. In addition, there are no studies focusing on the use of AHP for integrated maintenance prioritization and budget optimization based on expert opinions for cross-asset systems consisting of road and water pipe assets. Developing a maintenance priority for cross-assets is very important for asset management decisions, especially when working with strictly limited budgets. Therefore, the present study developed an integrated fund allocation model for cross-assets based on the responses of the asset managers involved in the management of roads and water pipes using AHP. The opinions of the asset managers were used to derive the relative weights for the resource allocation among asset items in the cross-asset system. The process for trade-off analysis has been demonstrated among the available maintenance alternatives for road asset and water pipe asset maintenance, considering their relative priorities and benefit/cost values, facilitating asset managers to choose the best maintenance option within the available budget. The findings of this study will benefit asset managers in deciding the maintenance fund optimization for a cross-asset system consisting of road assets and water pipe assets.

3. Research Methodology

This section presents the methods of data collection and AHP analysis conducted to develop a scientific method for maintenance prioritization ranking of a cross-asset system consisting of road assets and water pipe assets for a systematic fund allocation. Further, the implementation of the results of the AHP analysis to optimize the fund allocation within the project is also outlined in this section.

3.1. Data Collection (Questionnaire Development)

Maintenance decisions on road pavements and other related assets are generally decided based on many factors, including technical details and socio-economic factors. These factors vary according to the country and region, as they are highly dependent on the behavior of the users and the management authorities. Therefore, this study presents a case study conducted in Sri Lanka to establish a hierarchical structure for cross-asset maintenance, considering road pavement and underground water pipes as critical assets. Two questionnaires, one each for road and water pipe assets, were developed to collect the opinions of the asset managers. The selected participants of these questionnaire surveys possess significant industry experience in the management of either roads (Road Development Authority (RDA) of Sri Lanka) or water pipes (National Water Supply and Drainage Board (NWSDB) of Sri Lanka). First, the participants were requested to select the critical criteria, most preferred maintenance options (maintenance levels), and sub-options (elements in the asset system that require priority in maintenance) from a list of items for each asset. For instance, eight criteria were given in the questionnaire for road asset managers, including agency cost, condition of infrastructure, user cost, environmental considerations, hazard mitigation, safety, mobility, and level of service of the road.

The criteria options given for the water pipe asset managers included agency cost, condition of the pipe network, safety, system pressure, hazard mitigation, environmental considerations, level of service of the pipe network, material availability, actions of the road agency, political needs, and water quality. Road asset elements were classified into four categories: pavements, structures, traffic facilities, and corridor assets. The pavements include all pavement types covering sealed and unsealed roads, while the structures group includes bridges, culverts, and tunnels. The main items falling into traffic facilities include signs, traffic signals, intelligent transport systems, devices and delineations, lighting, safety barriers, and guideposts. The corridor (roadside) assets include drainage, batters, fences, rest areas, litter control, vegetation management, and management of cultural heritage. The asset elements considered for the pipe assets include pipes, fittings, air valves, scouring valves, gate washouts, section valves, ferrules, house connections, clamp saddles, and water meters.

The maintenance options considered for the road pavements include ‘rehabilitation (RHB),’ ‘regulation + resurfacing (REG+RSF),’ ‘resurfacing (RSF),’ and ‘any other maintenance option (OTH).’ All the other elements in the road assets and water pipe assets have four choices for maintenance: ‘replacement (REP),’ ‘major maintenance (MJR),’ ‘minor maintenance (MNR),’ and ‘any other maintenance option (OTH).’ These lists of items for each criterion, options (asset elements), and sub-options (maintenance options) were derived from relevant literature and also based on the expert opinions obtained at the stage of designing the questionnaires [18, 34, 39]. The respondents were given the authority to add any new item to the list in case the given items in the list do not match their intended response.

The respondents were then requested to conduct a pair-wise comparison of the criteria, options, and sub-options using the AHP judgment scale. The fundamental scale in Table 1, which shows the judgment values and relevant numerical values, was given to the respondents for pair-wise comparison. It should be noted in Table 1 that the numbers 2, 4, 6, and 8 should be used to facilitate compromise between slightly differing judgments, and reciprocal values should be used when B is more important than A. Further, information regarding the current maintenance schedules and associated maintenance costs was also collected in the questionnaires. The responses given by the experts were used for the selection of criteria, options, and sub-options and, subsequently, for the development of the AHP models. The process for data collection is shown in Figure 3.

Table 1. The scale used in the AHP analysis [17]

Relative importance	Scale
A and B are equally important	1
A is weakly more important than B	3
A is strongly more important than B	5
A is very strongly more important than B	7
A is more important than B	9

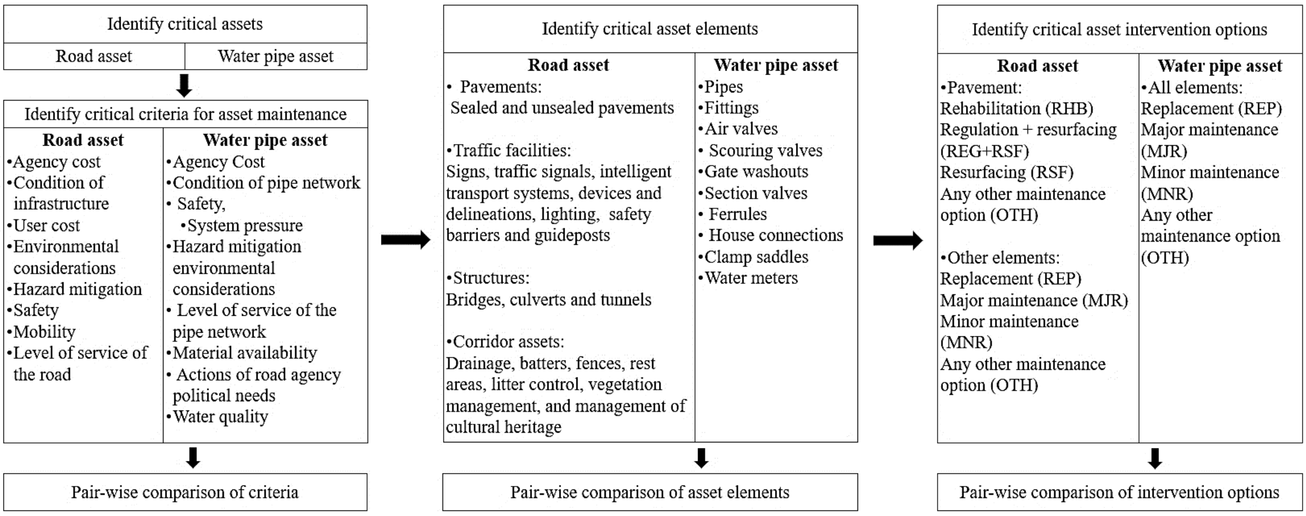

Figure 3. Process of data collection

The number of participants for the questionnaires on road and water pipe assets was 60 and 65, respectively. A total of 20 responses were received for each questionnaire, and the response rates for the questionnaire on road and water pipe assets were 33.3% and 30.8%, respectively.

3.2. Analysis of the Responses

The responses collected for the two questionnaires were analyzed individually to obtain the inputs for the AHP-based models. Of the total responses received, the most common six criteria, three options, and four sub-options by the respondents were selected for further analysis. Based on the outcome of the pair-wise comparison made by the respondents, pair-wise comparison matrices were developed, as shown in Equation 1 [25].

$$M = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}, a_{ii} = 1, a_{ji} = {}^{1}/_{a_{ij}}, a_{ij} \neq 0 \quad (1)$$

where a_{ij} is the result of pairwise comparison between attribute i as compared to attribute j and is assigned to the (i, j)th position of the comparison matrix M.

By considering each response, a representative judgment matrix needs to be calculated. According to Aidinidou et al. [40], the combination of the response judgments can be done either by taking the geometric mean of the comparisons or by a consensus vote on comparisons without performing a mathematical aggregation. In this study, the representative matrix was developed by taking the geometric mean of all the comparison values for each pair-wise comparison. The geometric mean was calculated by taking the nth root of the product of judgments, where n is the number of judgments [18]. In assigning values for pair-wise comparison of the options and sub-options, the values corresponding to each selected criterion were considered. Having calculated the representative pair-wise comparison matrices, the calculations were performed to find the criteria weights using column totals and a normalized matrix, as shown in Tables 2 and 3.

Table 2. Pair-wise comparison values and column totals

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
Criterion 1	a_1	a_2	a_3	a_4	a_5	a_6
Criterion 2	b_1	b_2	b_3	b_4	b_5	b_6
Criterion 3	c_1	c_2	c_3	c_4	c_5	c_6
Criterion 4	d_1	d_2	d_3	d_4	d_5	d_6
Criterion 5	e_1	e_2	e_3	e_4	e_5	e_6
Criterion 6	f_1	f_2	f_3	f_4	f_5	f_6
Column Total	$T_1=a_1+b_1+c_1+d_1+e_1+f_1$	$T_2=a_2+b_2+c_2+d_2+e_2+f_2$	$T_3=a_3+b_3+c_3+d_3+e_3+f_3$	$T_4=a_4+b_4+c_4+d_4+e_4+f_4$	$T_5=a_5+b_5+c_5+d_5+e_5+f_5$	$T_6=a_6+b_6+c_6+d_6+e_6+f_6$

Table 3. Normalized values and average criteria weights

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criteria Weight
Criterion 1	a_1/T_1	a_2/T_2	a_3/T_3	a_4/T_4	a_5/T_5	a_6/T_6	W_1=Average ($a_1/T_1,\dots, a_6/T_6$)
Criterion 2	b_1/T_1	b_2/T_2	b_3/T_3	b_4/T_4	b_5/T_5	b_6/T_6	W_2=Average ($b_1/T_1,\dots, b_6/T_6$)
Criterion 3	c_1/T_1	c_2/T_2	c_3/T_3	c_4/T_4	c_5/T_5	c_6/T_6	W_3=Average ($c_1/T_1,\dots, c_6/T_6$)
Criterion 4	d_1/T_1	d_2/T_2	d_3/T_3	d_4/T_4	d_5/T_5	d_6/T_6	W_4=Average ($d_1/T_1,\dots, d_6/T_6$)
Criterion 5	e_1/T_1	e_2/T_2	e_3/T_3	e_4/T_4	e_5/T_5	e_6/T_6	W_5=Average ($e_1/T_1,\dots, e_6/T_6$)
Criterion 6	f_1/T_1	f_2/T_2	f_3/T_3	f_4/T_4	f_5/T_5	f_6/T_6	W_6=Average ($f_1/T_1,\dots, f_6/T_6$)

After calculating the criteria weights, the normalized matrices for different maintenance options were also formulated using a similar method. Pair-wise comparisons were conducted between different options, considering each criterion, and the maintenance option weights under each criterion were calculated to derive the normalized values (O_{ij}). Subsequently, the overall priority and the ranking were estimated, as shown in Table 4. A similar method of calculation adopted for options was also performed for sub-options, and the priority ranking of the sub-options was also evaluated, as shown in Table 5. To derive the normalized values S_{ij} in Table 5, pair-wise comparisons were conducted between different sub-options considering each criterion, and the sub-option weights under each criterion were calculated. The maintenance decision for roads and pipes is determined based on the relative weights assigned to specific criteria. Priority rankings for maintaining various elements within each asset group, along with rankings for different maintenance options for road pavement and water pipe elements, are then calculated by considering all critical criteria. The pair-wise comparison of the maintenance of asset elements was conducted only for the two critical asset elements (road pavement elements and water pipe elements), while the priorities of maintenance for other asset elements such as structures, traffic facilities, corridor items, pipe fittings, air valves, and water meters were determined based on the opinions of the asset managers based on their industry practices. The priority values for each asset element can be found in Section 4.4.

Table 4. Calculation of overall priorities and rankings of options

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Overall Priority	Rank
	W_1	**W_2**	**W_3**	**W_4**	**W_5**	**W_6**		
Option 1	O_{11}	O_{21}	O_{31}	O_{41}	O_{51}	O_{61}	P1 = ($W_1\times O_{11}+ W_2\times O_{21}+ \dots + W_6\times O_{61}$)	i
Option 2	O_{12}	O_{22}	O_{32}	O_{42}	O_{52}	O_{62}	P2 = ($W_1\times O_{12}+ W_2\times O_{22}+ \dots + W_6\times O_{62}$)	j
Option 3	O_{13}	O_{23}	O_{33}	O_{43}	O_{53}	O_{63}	P1 = ($W_1\times O_{13}+ W_2\times O_{23}+ \dots + W_6\times O_{63}$)	k

Table 5. Calculation of overall priorities and rankings of Sub options

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Overall Priority	Rank
	W_1	**W_2**	**W_3**	**W_4**	**W_5**	**W_6**		
Sub-option 1	S_{11}	S_{21}	S_{31}	S_{41}	S_{51}	S_{61}	P1 = ($W_1\times S_{11}+ W_2\times S_{21}+ \dots + W_6\times S_{61}$)	s
Sub-option 2	S_{12}	S_{22}	S_{32}	S_{42}	S_{52}	S_{62}	P2 = ($W_1\times S_{12}+ W_2\times S_{22}+ \dots + W_6\times S_{62}$)	t
Sub-option 3	S_{13}	S_{23}	S_{33}	S_{43}	S_{53}	S_{63}	P1 = ($W_1\times S_{13}+ W_2\times S_{23}+ \dots + W_6\times S_{63}$)	u
Sub-option 4	S_{14}	S_{24}	S_{34}	S_{44}	S_{54}	S_{64}	P1 = ($W_1\times S_{14}+ W_2\times S_{24}+ \dots + W_6\times S_{64}$)	v

3.3. Evaluation of the Consistency of the Judgments

When conducting several comparisons one after the other, it is possible that illogical judgments are made by making the pair-wise comparison matrix inconsistent [41, 18]. For instance, when item A is preferred over item B and item B is preferred over item C, item A should be given a higher preference compared to item C to ensure consistency. Therefore, consistency ratio (CR) is used to evaluate the level of consistency. The threshold CR value is 10% for any comparison matrix, and when CR exceeds 10%, the judgments are considered illogical and cannot be considered for decision-making [42]. The CR was calculated using Equations 2 to 4 and Table 6 [17, 18, 43, 44].

$$CR = \frac{CI}{RI} \tag{2}$$

where CI is the consistency index and RI is a random index.

The consistency index was calculated using Equation 3:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{3}$$

where λ_{max} is the maximum eigenvalue and n is the number of criteria.

The λ_{max} value was evaluated from the arithmetic mean of the components of the vector *u*, which is defined as follows (Equation 4):

$$u_i = \sum_{i=1}^{n} M_{ij} W_i / W_i \tag{4}$$

where M_{ij} is the decision matrix used to compute the set of *n* weights W_i (i=1, …, n).

The RI is a value that depends on the matrix dimension. The values of RI for different *n* values are given in Table 6.

Table 6. The RI values for different n values

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

3.4. Cross-asset Resource Distribution

Initially, the asset management of individual assets (roads and water pipes) was considered, and based on the responses received from the asset managers, maintenance criteria, rankings of maintenance options, and asset elements were identified. These results were then combined into a single resource allocation model by assigning weights to the maintenance budgets for the two asset groups (roads and water pipes). The weights were assigned based on the annual maintenance budget allocations by the government for the two asset groups. Accordingly, the annual maintenance budget allocations for road and pipe assets are LKR Mn 112235 (USD Mn 344.7) and LKR Mn 55797 (USD Mn 171.4), respectively [45], indicating a ratio between the two asset groups as 2.55:1. Based on this ratio, the priority weights were calculated for road assets and water pipe assets as 0.7 and 0.3, respectively. A relatively similar ratio has been observed in other countries when allocating budgets for these two assets. For instance, a similar calculation showed that road: water pipe weighting factors from Victorian state government budget values are 0.65:0.35 [46]. Considering the calculated priority weights, the cost allocation and trade-off analysis were performed together for the two asset groups, and they are described in the following sections.

3.5. Maintenance Budget Allocation

The maintenance of infrastructure assets is generally associated with high budget requirements. Most of the time, the full budget required for the maintenance of the asset group is not allocated by the governing authorities due to the limitations in fund availability [47]. If the total required maintenance cost for the complete asset group is available (100% availability), the budget can be distributed among the asset elements depending on the ratio of the maintenance cost of the element to the total budget required. When the total required budget is not fully allocated (constrained budget), the distribution of the funds depending only on the maintenance cost will not be the optimum solution, and it is required to consider both maintenance priority and maintenance cost. To achieve this optimum cost allocation, the overall priorities and maintenance costs are integrated using Equations 5 to 8 [18].

$$PC = (1 - OP) \times \frac{c_i}{C} \tag{5}$$

where *PC* is the combined effect of priority and cost, OP is the overall priority of the asset element, c_i is the required maintenance cost of the element, and *C* is the total required maintenance cost.

$$PC_n = \frac{PC}{\sum PC} \tag{6}$$

where PC_n is the normalized PC:

$$S = PC_n \times \Delta C \tag{7}$$

where S is the budget shortfall allocation, and ΔC is the budget shortfall (difference in the required total budget and available total budget)

$$Percentage\ constrained\ budget = \frac{c_i - S}{\sum(c_i - S)} \tag{8}$$

These percentage-constrained budget values can be used for the optimum maintenance fund allocation. The unconstrained budget allocation is the proportion of the maintenance cost of each asset element to the total budget required. In this study, it is assumed that the total required budget is 100 million Sri Lankan rupees (LKR Mn 100 = USD Mn 0.3) and the constrained budget is LKR Mn 60 (USD Mn 0.18), leading to a total budget shortfall of LKR Mn 40 (USD Mn 0.12). Accordingly, the percentages of constrained budget allocation based on the priority values were calculated.

3.6. Trade-off Analysis

When budget constraints are applied, road asset managers need to prioritize the options, justify budget allocations among maintenance programs related to different assets, and ensure an acceptable level of service (LOS) for all the asset elements [48]. As a result of the prioritization process, which is usually based on cost, some activities are not performed, or cheaper treatment options with short service lives are often selected [18]. To maintain the optimum serviceability of the asset group, a trade-off among the intervention options of all the asset elements is performed considering both the priority of the LOS and maintenance cost values. Through prioritization and trade-off analyses, the benefits and costs of shifting funding from one asset group to another and the LOS possible at different expenditure levels could be assessed [18]. Optimization is then used to select the optimal combination of investment options across different assets that meet budget limits under the different maintenance programs. To perform the trade-off analysis, priorities of all asset elements need to be calculated. Each asset element should be assigned two or more maintenance levels, and the priorities of selecting each maintenance level and associated maintenance cost need to be determined. Weighted priority (WP) of asset element for different LOS and the WP/cost ratio (benefit/cost ratio) is assigned for each asset element, and different combinations of intervention levels are tested to determine the maximum benefit/cost value of the asset group [49].

In the current study, three maintenance levels were assigned for each asset element in the road asset and water pipe asset group, and their relative priority values were determined through the weighting factors obtained through the questionnaire data collection. The unit cost rates of maintenance for the different LOS of each asset element were collected from the asset managers, and asset element maintenance cost was calculated by considering the quantity of each asset element in the considered asset system. The WP values were calculated considering the LOS priorities and the asset group weights. The ratio between WP and maintenance cost (WP/cot) for each LOS in all asset elements was calculated, and all possible maintenance alternatives in the asset system were considered for the trade-off analysis. As each asset group (roads and water pipes) has four critical elements for maintenance and three maintenance options (LOS) for each element, altogether 81 alternatives are available when selecting an intervention combination for the asset group. This intervention combination can be shown by C_{pqrs} (where p, q, r, and s represent the LOS of pavements, structures, corridor items and traffic facilities, respectively for road assets; and pipes, fittings, air valves, and water meters, respectively for water pipe assets). The values for p, q, r, and s could be selected as 1, 2 or 3. Table 7 shows the notations used for the trade-off analysis. For an instance, combination C_{2113} in road asset maintenance will represent the intervention combination where LOS for pavements, structures, corridor items and traffic facilities are REG + RSF, REP, REP and MNR, respectively. Similarly, C_{2113} in water pipe asset maintenance will represent the intervention combination where LOS for pipes, fittings, air valves, and water meters are MJR, REP, REP and MNR, respectively.

Table 7. Different LOS levels and corresponding maintenance options for all asset elements

Road type	Asset element	LOS	Maintenance option
Road assets	Pavements (p)	1	RSF
		2	REG + RSF
		3	RHB
	Structures (q)	1	REP
		2	MJR
		3	MNR
	Corridor items (r)	1	REP
		2	MJR
		3	MNR
	Traffic facilities (s)	1	REP
		2	MJR
		3	MNR
Water pipe Assets	Pipes (p)	1	REP
		2	MJR
		3	MNR
	Fittings (q)	1	REP
		2	MJR
		3	MNR
	Air valve (r)	1	REP
		2	MJR
		3	MNR
	Water meters (s)	1	REP
		2	MJR
		3	MNR

Note: RSF - resurfacing, REG+RSF - regulation + resurfacing, RHB - rehabilitation, REP - replacement, MJR - major maintenance, and MNR - minor maintenance.

4. Results and Discussion

4.1. Responses for the Questionnaire on Road and Water Pipe Maintenance

The questionnaire responses were summarized based on the most critical criteria selected by the majority of the asset managers. Table 8 shows the six selected critical criteria, four selected critical asset elements, and the maintenance options for the road pavements and water pipes. These criteria for road pavement maintenance were selected by 50-95% of the respondents, while more than 85% of the respondents selected the asset elements and the maintenance options given in Table 8. Based on the responses of road asset managers, 'safety' has been selected as the first choice by 95% of the respondents. When it comes to pipe maintenance, the selected six criteria, four asset elements, and three maintenance options were chosen by 50%, 60%, and 90% of the respondents, respectively. The 'condition of pipe network' was selected as the first choice by 70% of the respondents.

Table 8. Selected criteria, elements, and maintenance options for road asset and pipe asset maintenance

Item	Road asset elements	Pipe asset elements
Selected critical criteria	I. Safety II. Hazard mitigation III. Agency cost IV. Environmental considerations V. mobility VI. Condition of road infrastructure	I. Condition of a pipe network II. System pressure III. Level of service IV. Water quality V. Agency cost VI. Safety
Selected asset elements	I. Pavements II. Structures III. Corridor items IV. Traffic facilities	I. Pipes II. Fittings III. Air valves IV. Water meters
Selected maintenance options	• *For Pavement Elements:* I. Resurfacing (RSF) II. Regulation + Resurfacing (REG + RSF) III. Rehabilitation (RHB) • *For Other Elements:* I. Replacement (REP) II. Major maintenance (MJR) III. Minor maintenance (MNR)	• *For All Elements:* I. Replacement (REP) II. Major maintenance (MJR) III. Minor maintenance (MNR)

Based on the criteria choices of the two asset groups, it could be observed that respondents have identified the condition of the infrastructure, agency cost, and safety as critical assets for both asset groups. Although 'safety' has been selected as the first choice by the majority of the road asset managers, it has been selected as the last choice by the water pipe asset managers. On the contrary, the 'condition of infrastructure' has been selected as the first choice by water pipe asset managers, whereas it has been selected as the last choice by road asset managers. Furthermore, the agency cost has been selected as the third choice in road asset maintenance, whereas it is the fifth choice when it comes to pipe asset maintenance. The differences in these preferences are due to the different driving factors, such as cost and reliability, in these two asset groups. A similar behavior has been observed by Abu Samra et al. [36], where the road interventions were driven by cost because of the ability to undertake cost-effective early interventions, whereas the water network interventions were driven by reliability because of the actions required to maintain an uninterrupted service. The asset group choices by the respondents to the questionnaires cover all the critical elements in each asset group. The pavement element in the road asset and the pipe element in the water pipe asset have been selected by the majority of the respondents as the critical elements for maintenance fund allocation. The optimal maintenance option selected for road pavements is 'resurfacing,' and the optimal selection for other elements in the road asset is 'replacement.' The optimal maintenance option selected for all the elements in water pipes is 'replacement.' Previous studies conducted on road assets or pipe asset maintenance have also observed similar selections of criteria, critical asset elements, and maintenance options [18, 34, 39, 50].

4.2. Pair-wise Comparisons and Criteria Weights for Asset Maintenance

Table 9 shows the representative matrix showing pair-wise comparison judgments of the critical criteria for road asset maintenance. Each element in the representative matrix was calculated by taking the geometric mean of all the responses.

Table 9. Relative priorities of criteria for road asset maintenance

Criterion		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
		Safety	**Hazard mitigation**	**Agency cost**	**Environmental considerations**	**Mobility**	**Condition of road infrastructure**
Criterion 1	Safety	1.00	3.32	2.94	4.08	3.12	2.88
Criterion 2	Hazard mitigation	0.30	1.00	3.57	2.24	1.52	2.28
Criterion 3	Agency cost	0.34	0.28	1.00	2.96	1.69	1.64
Criterion 4	Environmental considerations	0.24	0.45	0.34	1.00	1.47	0.45
Criterion 5	Mobility	0.32	0.66	0.59	0.68	1.00	0.44
Criterion 6	Condition of road infrastructure	0.35	0.44	0.61	2.21	2.27	1.00
	Column total	2.55	6.14	9.05	13.17	11.07	8.70

The CR value for the above judgment matrix is 7.13% (< 10%) and this value can be considered acceptable [17]. Table 10 shows the calculated normalized matrix for selected criteria and the final criteria weights for road maintenance decisions. According to the road asset managers, safety is the most critical criterion in road maintenance, with a criterion weight of 36%, while mobility and environmental considerations are the least critical, with criterion weights of 8% for each criterion. This is consistent with the previous findings as safety has been given the priority in road maintenance projects. For an instance, government road management authorities, such as Vicroads, gives the highest priority to safety in the road maintenance projects [51].

In a study conducted by Bhuiyan et al. [22] to rank four maintenance projects on highways, the crash (accident) rate, which is categorized under the 'safety' criteria in the current study, recorded the highest priority. Abu Samra et al. [36] conducted a study to develop a decision support tool for intervention planning for integrated road and water networks and they also recorded safety and the number of road users as the highest priorities in decision-making. Chaipetch et al. [27] found that economic factors (agency cost) are more important in decision-making in road assets compared to the engineering factors (asset condition and mobility), and these findings are consistent with the findings of the present study. On the other hand, few other studies have found that road pavement condition has the highest priority in road maintenance decisions [21, 24, 28] and this is contradictory to the findings of this study. These studies claim that pavement condition is more important because the serviceability and investments for maintenance on road assets are typically decided based on the pavement condition. However, it should be noted that the expert opinions are made based on the asset management practices and the available resources (funds). As the current study was conducted in Sri Lanka where only limited budgets are available for the high demand of road maintenance, the safety has become the dominant criterion for maintenance decisions.

Table 10. Criteria weights for road maintenance

Criterion	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criteria weight
	Safety	**Hazard mitigation**	**Agency cost**	**Environmental considerations**	**Mobility**	**Condition of infrastructure**	
Safety	0.39	0.54	0.32	0.31	0.28	0.33	0.36
Hazard mitigation	0.12	0.16	0.39	0.17	0.14	0.26	0.21
Agency cost	0.13	0.05	0.11	0.22	0.15	0.19	0.14
Environmental considerations	0.10	0.07	0.04	0.08	0.13	0.05	0.08
Mobility	0.13	0.11	0.07	0.05	0.09	0.05	0.08
Condition of infrastructure	0.14	0.07	0.07	0.17	0.21	0.11	0.13

Table 11 shows the representative matrix showing pair-wise comparison judgments of the critical criteria in pipe maintenance. The CR value for the judgment matrix is 5.53 (< 10%) and could be considered as acceptable.

Table 11. Relative priorities of criteria for water pipe maintenance

Criterion		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
		Condition of pipe network	**System pressure**	**Level of service**	**Water quality**	**Agency cost**	**Safety**
Criterion 1	Condition of pipe network	1.00	1.80	1.22	1.57	2.22	1.23
Criterion 2	System pressure	0.56	1.00	1.15	1.05	1.61	0.97
Criterion 3	Level of service	0.82	0.87	1.00	1.54	3.35	0.50
Criterion 4	Water quality	0.64	0.95	0.65	1.00	3.57	1.33
Criterion 5	Agency cost	0.45	0.62	0.30	0.28	1.00	0.97
Criterion 6	Safety	0.81	1.03	2.00	0.75	1.03	1.00
	Column total	4.27	6.28	6.32	6.19	12.79	6.00

Table 12 shows the calculated normalized matrix of criteria and the criteria weights for the water pipe maintenance decisions. The criterion weights are more fairly distributed among the six criteria. According to Table 12, the condition of the pipe has the maximum criterion weight of 22%, while agency cost has the minimum criterion weight of 9%. Water supply is considered a fundamental service for users, and hence, the authorities try to provide uninterrupted service throughout without giving much priority to the cost. Abu Samra et al. [36] also found that water pipes are more reliability-driven than cost-driven. This may be the reason for allocating higher weights for the condition of the pipe network than the agency cost in deciding the critical criteria for maintenance. Further, some other studies [30, 34] have found that physical and operational factors of pipe networks have high priorities for pipe maintenance. This is because water networks are expected to perform their service despite of the costs due to its high importance to the existence of the society. In the present study, high-priority values were observed for the criteria such as condition of the pipe network, level of service, water quality and system pressure, and these are consistent with the above findings. Aşchilean et al. [33] found that pressure losses and the cost are critical criteria with heist weights in decisions related to water pipe maintenance. The results derived in the present study are purely based on an expert survey and the responses are case-specific based on local practices and resource (fund) allocation. It can be noted that the order of the criteria selections in both assets does not exactly match with their ranking based on the relative priorities. This is because, the relative priorities are derived considering pair-wise comparisons by all responses while the top preferences are selected based on the majority of the responses.

Table 12. Criteria weights for water pipe maintenance

Criterion	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criteria weight
	Condition of pipe network	System pressure	Level of service	Water quality	Agency cost	Safety	
Condition of pipe network	0.23	0.29	0.19	0.25	0.17	0.20	0.22
System pressure	0.13	0.16	0.18	0.17	0.13	0.16	0.15
Level of service	0.19	0.14	0.16	0.25	0.26	0.08	0.18
Water quality	0.15	0.15	0.10	0.16	0.28	0.22	0.18
Agency cost	0.11	0.10	0.05	0.05	0.08	0.16	0.09
Safety	0.19	0.16	0.32	0.12	0.08	0.17	0.17

4.3. Pair-Wise Comparisons of Asset Elements and Maintenance Options

Six representative matrices showing pair-wise comparison judgments of the asset element options with respect to each criterion for road asset maintenance and water pipe asset maintenance are given in Tables 13 and 14, respectively. The CR values of all the six matrices for both road asset maintenance and water pipe asset maintenance are less than 10% and are in the acceptable region.

Table 13. Pair-wise comparison of road asset elements for maintenance

Criterion	Option	Structures	Pavements	Corridor items	Traffic facilities	CR (%)
Safety	Structures	1.00	0.89	2.01	1.06	2.46
	Pavements	1.13	1.00	2.31	1.88	
	Corridor items	0.50	0.43	1.00	1.20	
	Traffic facilities	0.95	0.53	0.83	1.00	
Hazard mitigation	Structures	1.00	0.77	2.42	0.85	3.99
	Pavements	1.30	1.00	2.65	2.13	
	Corridor items	0.41	0.38	1.00	1.03	
	Traffic facilities	1.18	0.47	0.97	1.00	
Agency cost	Structures	1.00	0.63	3.06	1.49	3.01
	Pavements	1.58	1.00	3.37	2.74	
	Corridor items	0.33	0.30	1.00	1.26	
	Traffic facilities	0.67	0.36	0.79	1.00	

Environmental considerations	Structures	1.00	0.96	1.93	1.62	3.66
	Pavements	1.04	1.00	2.21	2.14	
	Corridor items	0.52	0.45	1.00	2.11	
	Traffic facilities	0.62	0.47	0.47	1.00	
Mobility	Structures	1.00	0.80	2.60	0.83	9.96
	Pavements	1.26	1.00	3.52	2.36	
	Corridor items	0.39	0.28	1.00	1.10	
	Traffic facilities	1.20	0.42	0.91	1.00	
Condition of infrastructure	Structures	1.00	0.93	3.74	1.24	5.39
	Pavements	1.07	1.00	2.77	2.42	
	Corridor items	0.27	0.36	1.00	1.20	
	Traffic facilities	0.80	0.41	0.83	1.00	

Table 14. Pair-wise comparison of pipe asset elements for maintenance

Criterion	Option	Pipes	Fittings	Air valve	Water meters	CR (%)
Condition of pipe network	Pipes	1.00	1.36	2.12	2.37	0.67
	Fittings	0.73	1.00	2.15	2.65	
	Air valve	0.47	0.47	1.00	1.17	
	Water meters	0.42	0.38	0.86	1.00	
System pressure	Pipes	1.00	2.00	2.30	1.50	2.48
	Fittings	0.50	1.00	1.61	1.53	
	Air valve	0.43	0.62	1.00	1.20	
	Water meters	0.67	0.65	0.83	1.00	
Level of service	Pipes	1.00	1.42	0.87	2.19	6.74
	Fittings	0.71	1.00	1.30	2.33	
	Air valve	1.14	0.77	1.00	0.77	
	Water meters	0.46	0.43	1.29	1.00	
Water quality	Pipes	1.00	0.93	1.74	2.10	2.68
	Fittings	1.08	1.00	2.33	2.00	
	Air valve	0.57	0.43	1.00	0.50	
	Water meters	0.48	0.50	2.00	1.00	
Agency cost	Pipes	1.00	1.60	1.50	2.05	3.55
	Fittings	0.63	1.00	1.58	2.33	
	Air valve	0.67	0.63	1.00	1.00	
	Water meters	0.49	0.43	1.00	1.00	
Safety	Pipes	1.00	0.81	1.50	2.08	1.05
	Fittings	1.23	1.00	2.00	3.33	
	Air valve	0.67	0.50	1.00	1.00	
	Water meters	0.48	0.30	1.00	1.00	

Six representative matrices showing pair-wise comparison judgments of the maintenance options with respect to each criterion for road pavement element maintenance and water pipe element maintenance are given in Tables 15 and 16, respectively. According to Tables 15 and 16, the CR values of all the matrices for both assets are within the acceptable range of 10%.

Table 15. Pair-wise comparison of maintenance options for road pavement maintenance

Criterion	Maintenance option	RSF	REG + RSF	RHB	CR (%)
Safety	RSF	1.00	1.38	2.16	0.001
	REG + RSF	0.72	1.00	1.57	
	RHB	0.46	0.64	1.00	
Hazard mitigation	RSF	1.00	1.17	1.49	0.16
	REG + RSF	0.85	1.00	1.44	
	RHB	0.67	0.70	1.00	
Agency cost	RSF	1.00	0.83	1.10	2.53
	REG + RSF	1.21	1.00	0.81	
	RHB	0.91	1.23	1.00	
Environmental considerations	RSF	1.00	1.03	1.51	0.48
	REG + RSF	0.97	1.00	1.19	
	RHB	0.66	0.84	1.00	
Mobility	RSF	1.00	2.01	2.12	8.02
	REG + RSF	0.50	1.00	2.51	
	RHB	0.47	0.40	1.00	
Condition of infrastructure	RSF	1.00	1.41	1.59	3.22
	REG + RSF	0.71	1.00	1.94	
	RHB	0.63	0.52	1.00	

Table 16. Pair-wise comparison of maintenance options for water pipe element maintenance

Criteria	Maintenance options	MJR	REP	MNR	CR (%)
Condition of pipe network	REP	1.00	2.82	2.90	9.32
	MJR	0.36	1.00	1.58	
	MNR	0.28	0.96	1.00	
System pressure	REP	1.00	1.63	1.76	4.55
	MJR	0.62	1.00	1.63	
	MNR	0.57	0.66	1.00	
Level of service	REP	1.00	1.69	1.52	5.95
	MJR	0.59	1.00	0.97	
	MNR	0.66	1.22	1.00	
Water quality	REP	1.00	1.53	1.69	2.95
	MJR	0.66	1.00	1.35	
	MNR	0.59	0.79	1.00	
Agency cost	REP	1.00	3.30	3.50	9.58
	MJR	0.30	1.00	1.77	
	MNR	0.27	0.74	1.00	
Safety	REP	1.00	1.45	1.88	8.87
	MJR	0.71	1.00	1.28	
	MNR	0.53	0.97	1.00	

4.4. Ranking of the Asset Elements for Maintenance

The six different pair-wise comparison matrices for asset element options, which were summarized under six critical criteria for each asset, were combined to get the relative importance of the asset elements (options). This process is called synthesis, and it determines the overall option priorities and the option rankings. The synthesis of the criteria weights with the normalized option values for asset options, the corresponding overall priority, and the ranking of the maintenance options for road and water pipe maintenance are shown in Tables 17 and 18, respectively. The distribution of the weights for each asset element in road and water pipe asset groups is shown in Figures 4 and 5, respectively. According to Table 17 and Figure 4, ‘pavements’ are identified as the most important asset element for road asset maintenance, while ‘corridor items’ are characterized as the least priority item. For the road asset group, pavements have a higher asset weight compared to the other asset elements, making the overall priority value of the pavement elements higher than the others. The pavement is the basic element that decides the condition and functionality of the whole road asset. Therefore, it has scored a higher priority in maintenance compared to the other asset elements, such as corridor items. A similar trend was observed by Orugbo et al. [26], where ‘carriageway’ scored the highest weight while ‘roadside telephone’ scored the lowest weight when evaluating the asset item maintenance priorities. For water pipe maintenance (Table 18 and Figure 5), the most and least prioritized asset elements are “pipes” and “water meters,” respectively. Pipes and fittings are often considered together for maintenance, and the result from the present study also confirms the same with almost similar priority values. The pipes and fittings have higher asset element weights as they are the basic elements that decide the condition and functionality of the whole pipe network. This has led them to score considerably higher weights compared to other asset elements, such as air valves and water meters. A higher maintenance priority is given to pipe elements due to their high failure rate compared to the other components [52].

Table 17. Synthesis, overall priority, and ranking of road asset elements for maintenance

Criterion	Safety	Hazard mitigation	Agency cost	Environmental considerations	Mobility	Condition of infrastructure	Overall Priority	Rank
Criterion weight	**0.36**	**0.21**	**0.14**	**0.08**	**0.08**	**0.13**		
Structures	0.28	0.27	0.29	0.31	0.26	0.33	0.29	2
Pavements	0.35	0.38	0.43	0.35	0.40	0.36	0.37	1
Corridor items	0.17	0.15	0.13	0.20	0.14	0.14	0.16	4
Traffic facilities	0.20	0.20	0.15	0.15	0.20	0.17	0.18	3

Table 18. Synthesis, overall priority, and ranking of water pipe asset elements for maintenance

Criterion	Condition of pipe network	System pressure	Level of service	Water quality	Agency cost	Safety	Overall Priority	Rank
Criterion weight	**0.22**	**0.15**	**0.18**	**0.18**	**0.09**	**0.17**		
Pipes	0.38	0.31	0.32	0.35	0.29	0.29	0.34	1
Fittings	0.25	0.29	0.35	0.29	0.39	0.39	0.32	2
Air valve	0.18	0.23	0.14	0.19	0.18	0.18	0.18	3
Water meters	0.19	0.18	0.20	0.16	0.14	0.14	0.17	4

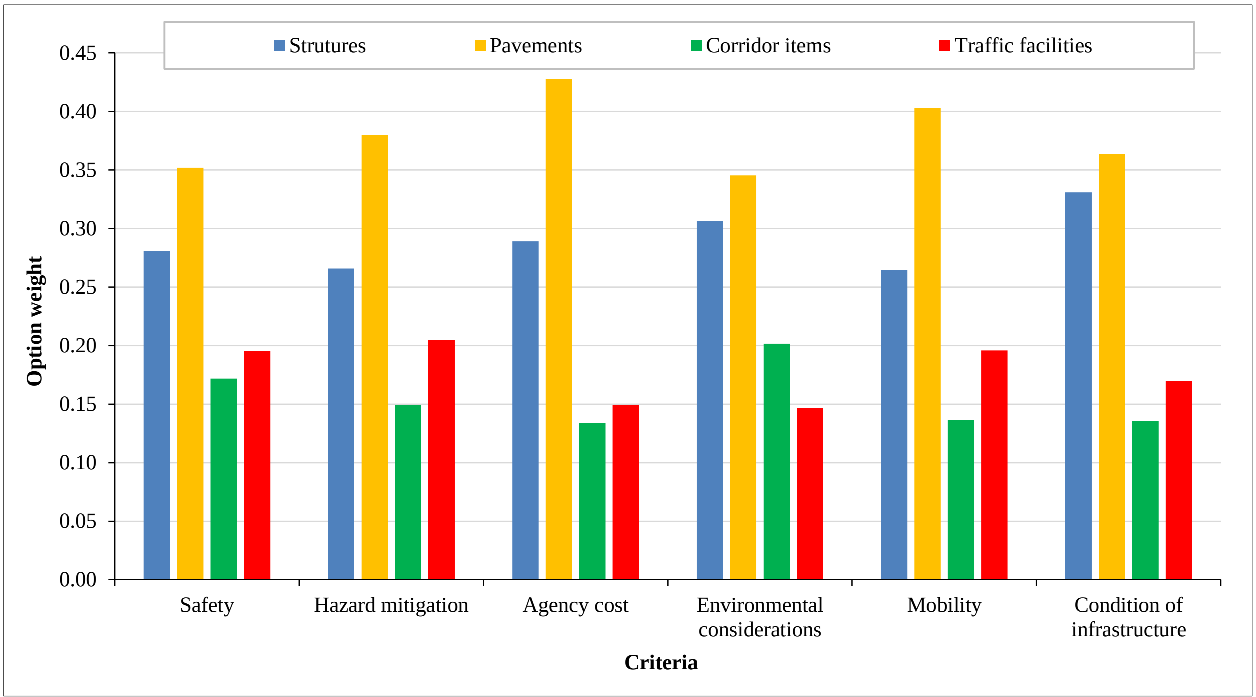

Figure 4. Distribution of weights for road asset elements under each criterion

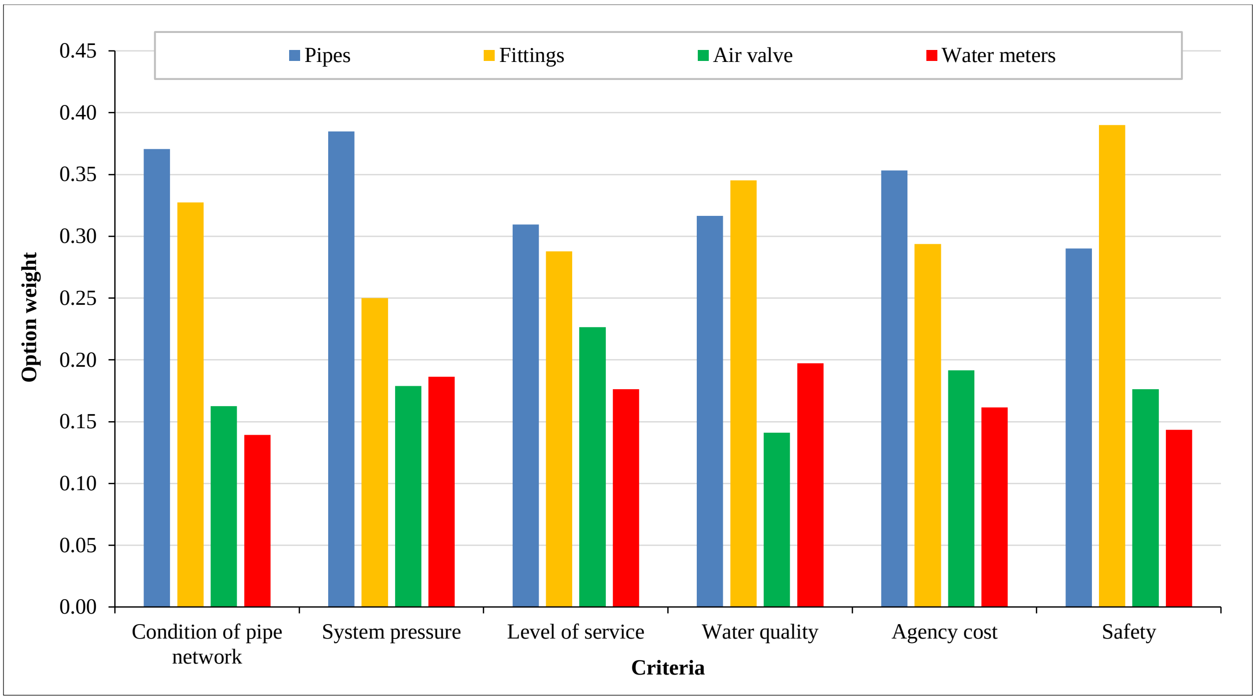

Figure 5. Distribution of weights for water pipe asset elements under each criterion

4.5. Ranking of Maintenance Options

The six different pair-wise comparison matrices of maintenance options resulting from the six critical criteria in each asset group were combined to get the relative importance of the maintenance options. The synthesis of the criteria weights with the normalized option values and the corresponding overall priority and ranking of the maintenance options for road pavement maintenance and water pipe maintenance are shown in Tables 19 and 20, respectively. The distribution of the weights for each maintenance option in the road asset group and water pipe asset groups are shown in Figures 6 and 7, respectively. According to Table 19 and Figure 6, the maintenance option 'resurfacing (RSF)' has been identified as the most influential maintenance option (overall priority of 42%) for the road pavements, while 'rehabilitation (RHB)' has been identified as the least influencing maintenance option (overall priority of 24%). This is because resurfacing is generally a low-cost maintenance treatment compared to other options, and frequent resurfacing prevents roads from further deterioration. Previous studies [53, 54] also have found similar priority rankings for road maintenance. Due to the differences in maintenance costs, road asset managers prefer to attend low-cost early-stage maintenance activities rather than waiting for expensive rehabilitation activities at a later stage [36, 55, 56].

Table 19. Synthesis, overall priority, and ranking of road pavement element maintenance options

		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6		
		Safety	**Hazard mitigation**	**Agency cost**	**Environmental considerations**	**Mobility**	**Condition of infrastructure**	**Overall Priority**	**Rank**
		0.36	**0.21**	**0.14**	**0.08**	**0.08**	**0.13**		
Option 1	RSF	0.46	0.39	0.32	0.38	0.49	0.42	0.42	1
Option 2	REG + RSF	0.33	0.35	0.33	0.35	0.33	0.36	0.34	2
Option 3	RHB	0.21	0.25	0.35	0.27	0.18	0.22	0.24	3

Table 20. Synthesis, overall priority, and ranking of water pipe element maintenance options

		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6		
		Condition of pipe network	**System pressure**	**Level of service**	**Water quality**	**Agency cost**	**Safety**	**Overall Priority**	**Rank**
		0.22	**0.15**	**0.18**	**0.18**	**0.09**	**0.17**		
Option 1	REP	0.58	0.45	0.44	0.44	0.62	0.44	0.49	1
Option 2	MJR	0.24	0.32	0.27	0.31	0.22	0.31	0.28	2
Option 3	MNR	0.18	0.23	0.30	0.25	0.16	0.25	0.23	3

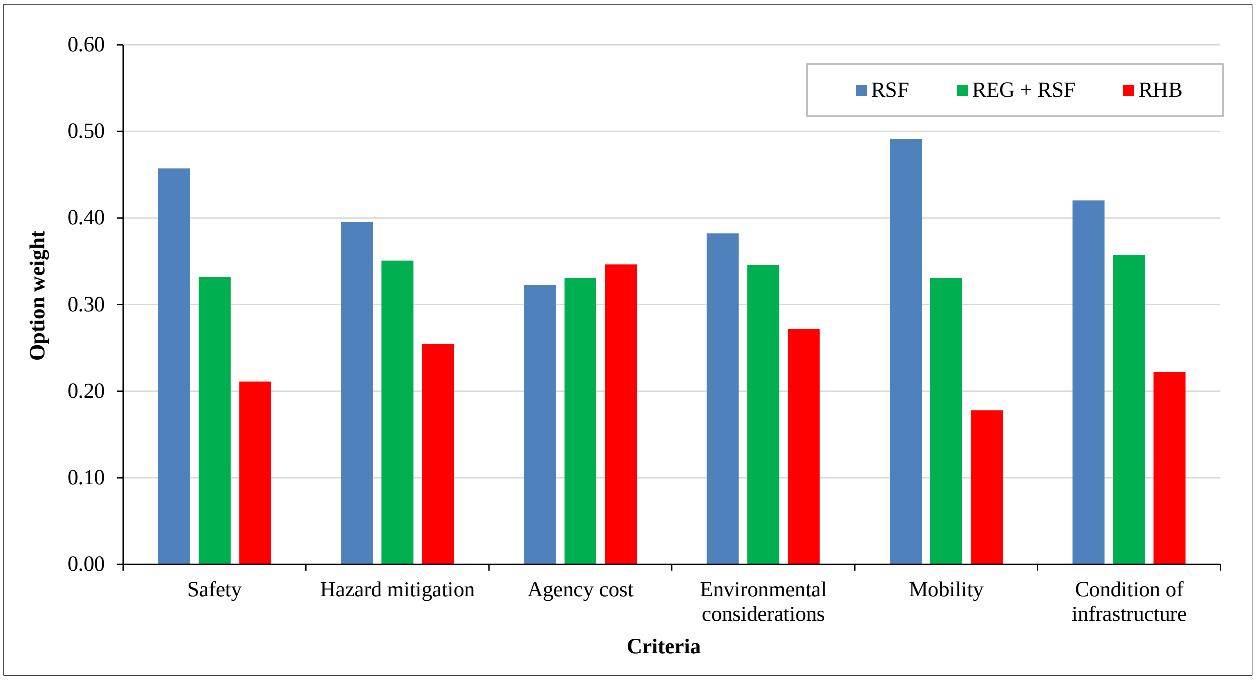

Figure 6. Distribution of weights for maintenance options in road assets under each criterion

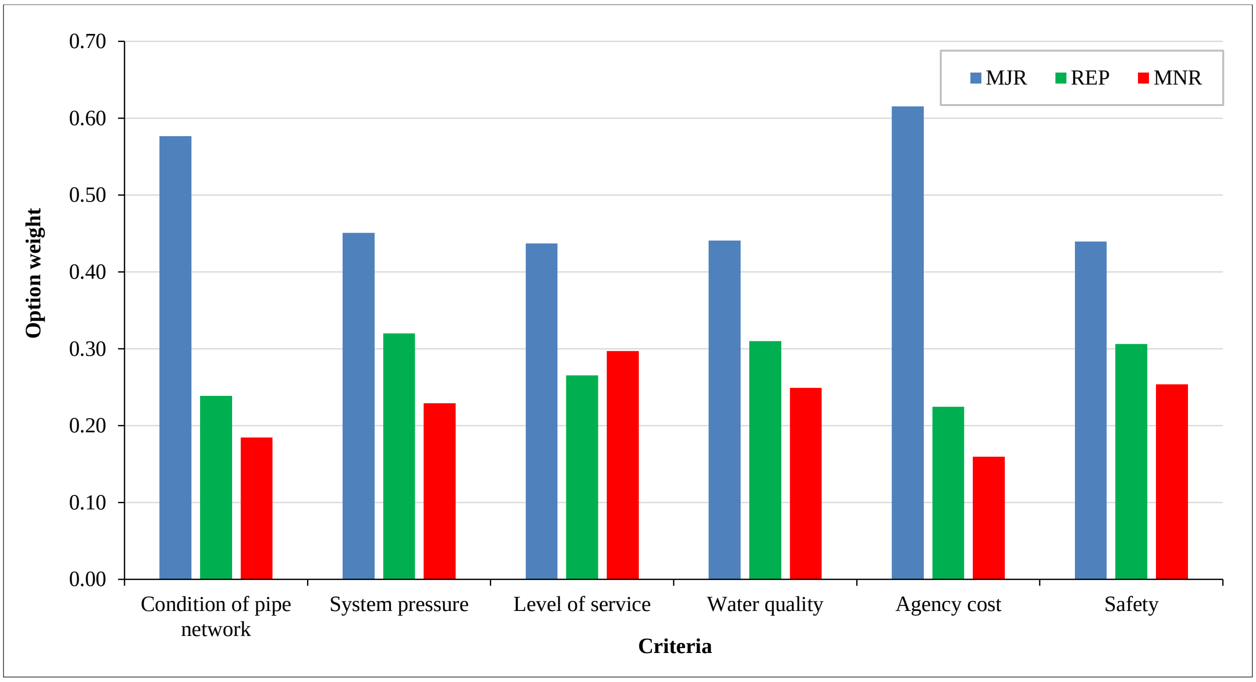

Figure 7. Distribution of weights for maintenance options in water pipe assets under each criterion

According to Table 20 and Figure 7, the most critical maintenance option for water pipe elements is 'replacement (REP) (overall priority of 49%),' while 'minor maintenance (MNR)' (overall priority of 23%) is identified as the least critical maintenance option. This is because the maintenance of the pipes associated with the roads is a complex and expensive process. Unlike road assets, pipe maintenance needs demolition of the road corridor, and hence asset managers do not prefer frequent minor maintenance works. Therefore, water pipe asset managers have chosen replacement over other maintenance activities since the longest service before maintenance is associated with replacement, despite the high cost involved for the replacement. This difference in the preferences of the asset managers can be described according to the drivers and procedures of the maintenance of these two different assets. According to Abu Samra et al. [36], road maintenance decisions on road assets are biased more toward the maintenance cost as the road agencies prefer to undertake a cost-effective intervention earlier rather than postponing the intervention and undertaking costly road rehabilitation at a later stage. On the contrary, decisions on water networks are made based on reliability to ensure minimum service outages and repairs. In addition, pavement maintenance is less complicated when compared to underground pipe maintenance, mainly due to accessibility and service interruptions [57]. As a result, although road asset managers prefer to conduct frequent small-scale maintenance activities, pipe asset managers tend to wait until the maximum service life is experienced to perform until failure.

4.6. Sensitivity Analysis

The results of asset maintenance decisions are influenced by multiple criteria. The purpose of the sensitivity analysis is to explore the criteria having significant effects on the maintenance decision-making of each asset group, considering maintenance options and the asset elements. The sensitivity of the top three criteria (the criteria having the highest criteria weights) was analyzed for both road asset and water pipe asset groups. Each criterion weight was changed by ±10%, and the other criteria weights were adjusted, preserving the ration between the weights to make the total criteria weight to be 1.0. The percentage change in the priority weights of the maintenance options and the asset elements in each asset group was calculated accordingly, as shown in Table 21. According to Table 21, when the criteria weights were changed by 10%, the percentage changes in the final priority weights in all options and asset elements were negligible (< 1%). Hence, the ranking of the asset maintenance options, and asset elements remained unchanged with the change in the criteria weights by 10%. The results from the sensitivity analysis for maintenance options and asset elements were consistent with the weighting values of maintenance decision-making criteria.

Table 21. Sensitivity analysis for top three criteria for road and water pipe assets

Asset Group	Top three criteria	% change in criteria weight	% change in maintenance option priority weight			% change in asset element priority weight			
			Option 1	Option 2	Option 3	Element 1	Element 2	Element 3	Element 4
Road asset	C1: Safety	+10%	-0.23	0.05	0.18	0.03	0.12	-0.09	-0.07
		-10%	0.23	-0.05	-0.18	-0.03	-0.12	0.09	0.07
	C2: Hazard mitigation	+10%	0.06	-0.03	-0.03	0.05	-0.02	0.02	-0.06
		-10%	-0.06	0.03	0.03	-0.05	0.02	-0.02	0.06
	C3: Agency cost	+10%	0.16	0.01	-0.17	0.00	-0.09	0.04	0.06
		-10%	-0.16	-0.01	0.17	0.00	0.09	-0.04	-0.06
Water pipe asset	C1: Condition of pipe network	+10%	-0.26	0.12	0.14	-0.10	-0.02	0.04	0.08
		-10%	0.26	-0.12	-0.14	0.10	0.02	-0.04	-0.08
	C2: Level of service	+10%	0.11	0.03	-0.14	0.06	0.07	-0.11	-0.02
		-10%	-0.11	-0.03	0.14	-0.06	-0.07	0.11	0.02
	C3: Water quality	+10%	0.27	0.05	0.06	0.17	0.08	0.13	0.01
		-10%	-0.27	-0.05	-0.06	-0.17	-0.08	-0.13	-0.01

4.7. Maintenance Budget Allocation

As highlighted in the methodology (section 3.5), a total budget of LKR100 Mn (USD Mn 0.3) and a constrained budget of LKR 60 Mn (USD Mn 0.18) (with a budget shortfall of LKR 40 Mn (USD Mn 0.12)) were assumed in this study for the maintenance budget allocation. This percentage shortfall value was selected conservatively based on the average budget allocation shortfall values of the two assets in Sri Lanka, which is around 31% and 35% for the road and water pipe sectors, respectively [58, 59]. The constrained budget is distributed among the asset elements considering their priorities and maintenance costs. Table 22 shows the maintenance fund allocation for an asset system consisting of both road assets and water pipe assets. According to Table 22, when the constrained budgets are applied, the percentage fund allocations for pavements, structures and corridor items have increased between 0.2% and 10.3% compared to the unconstrained budget allocation. On the contrary, the budget allocation for the traffic facilities has reduced by 1.3% in the constrained budget compared to the unconstrained budget allocation in the road asset group. On the other hand, the fund allocations for all the elements in the water pipe asset group have recorded reductions in the constrained budget (2.0% to 5.9%) compared to unconstrained budget allocations. On the whole, based on the constrained budget, the budget allocation for the road asset group has increased by 5.1% compared to the unconstrained budget, whereas the fund allocation for pipe assets has reduced by 3.4% in the constrained budget compared to the unconstrained budget allocation.

Table 22. Maintenance fund allocation with a constrained budget

Asset group	Asset element	Maintenance budget (LKR Mn) (C)	Unconstrained budget allocation (%) %C = (C/Total cost) × 100	Overall priority (OP)	Priority effect on budget shortfall P=1-OP	The combined effect of priority & costs (EQ 5)	Normalized combined effect (%) (EQ 6)	Budget shortfall allocation (Mn) -Q (EQ7)	Constrained budget allocation (LKR Mn) X=C-Q	% Constrained budget allocation (Eq 8)	% change in constrained allocations compared to unconstrained funds
Road asset	Pavements	14.50	14.50	0.26	0.74	10.71	0.12	4.90	9.60	15.99	10.3
	Structures	11.50	11.50	0.20	0.80	9.20	0.11	4.21	7.29	12.15	5.6
	Traffic facilities	8.80	8.80	0.11	0.89	7.84	0.09	3.59	5.21	8.69	-1.3
	Corridor items	5.20	5.20	0.13	0.87	4.53	0.05	2.08	3.12	5.21	0.2
Water Pipe asset	Pipes	27.80	27.80	0.10	0.90	24.99	0.29	11.45	16.35	27.26	-2.0
	Fittings	10.20	10.20	0.10	0.90	9.22	0.11	4.22	5.98	9.96	-2.3
	Air valve	13.10	13.10	0.05	0.95	12.40	0.14	5.68	7.42	12.37	-5.6
	Water meters	8.90	8.90	0.05	0.95	8.46	0.10	3.87	5.03	8.38	-5.9
	Total	**100.00**	**100.00**	**1.00**	**7.00**	**87.34**	**1.00**	**40.00**	**60.00**	**100**	

The unconstrained maintenance budget values are purely based on the maintenance cost values of each asset element, whereas the constrained budget allocation values are derived based on both the maintenance cost values and the maintenance priority values. Therefore, the percentage distribution of the unconstrained budget allocation values has either increased or decreased when calculating the constrained budget values. Accordingly, around 2% of the total budget allocation has been shifted from the water pipe asset group to the road asset group when budgets are constrained, and the budget shortfall has been distributed among all the elements considering their maintenance priorities. The aggregation of different asset groups into a single cost allocation framework should be performed carefully while preserving their individual asset management goals. In the current study, the available budget for the maintenance of the integrated asset system was not fully available, while both asset groups needed investments for all asset elements in the system. Therefore, the overall objective of the study was to distribute the funds for all asset elements in a fair method while reaching the maximum benefit. With the derived relative priorities for asset groups and asset elements, the fund allocation was performed based on the combined effect of cost and priority value. When the full maintenance budget required for the maintenance of all asset elements becomes available, the fund allocation could be performed only considering the maintenance cost value without evaluating the relative priorities of the asset elements.

5. Case Study

A case study was conducted to demonstrate the proposed methodology for network-level fund optimization using trade-off analysis. The area selected for this study is in Dehiwala, Colombo, Sri Lanka, as shown in Figure 8. The road section considered for the case study is a 6.7 km long portion of Class A2 road from point A (6.8626° N, 79.8643° E) to point B (6.8107° N, 79.8824° E), as shown in Figure 8-b. The annual summary of the cost values spent on maintenance of elements for roads and pipe assets was collected from the asset maintenance authorities in the selected area, and the asset item priorities obtained through the questionnaire study were used for the analysis.

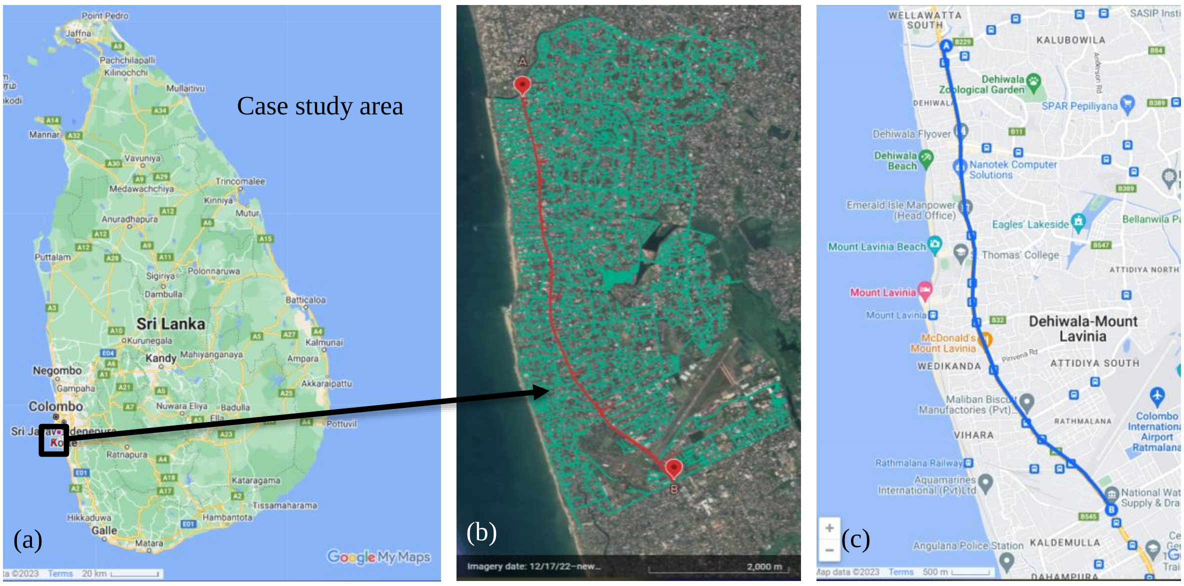

Figure 8. Case study area (a) Location on a map of Sri Lanka, (b) Selected road section and (c) Selected pipe network

Table 23 shows the total cost values required for each maintenance option and the WP/cost values calculated based on the priority values obtained from AHP analysis. According to Table 23, traffic facilities will have the highest WP/cost values due to their lower maintenance cost values compared to other elements in the road asset group. Although pavement elements scored the highest priority in the road asset group, they possess the lowest WP/cost value in the group due to the high unit cost for maintenance. In the pipe asset group, air valves resulted in the highest WP/cost due to the lower maintenance cost, while water meters recorded the lowest WP/cost value due to their high maintenance cost and least priority value. The total cost values and the WP/cost rates were used to conduct the trade-off analysis among the alternatives for each asset group. Accordingly, 81 maintenance alternatives are available for road and water pipe assets.

Table 23. The results of the trade-off analysis of the case study

Road class	Asset element	Asset item priority	Maintenance option	Maintenance option priority	Weighted priority (WP)	Total annual maintenance cost (LKR Mn)	% WP/cost ratio
Road Assets	Structures	0.29	REP	0.25	0.07	5.0	1.85
			MJR	0.35	0.10	4.0	3.31
			MNR	0.40	0.11	2.4	6.29
	Pavements	0.37	RSF	0.42	0.16	8.0	1.51
			REG + RSF	0.34	0.13	22.6	0.43
			RHB	0.24	0.09	58.8	0.12
	Corridor items	0.16	REP	0.25	0.04	4.0	0.98
			MJR	0.35	0.05	2.9	1.89
			MNR	0.40	0.06	1.0	6.16
	Traffic facilities	0.18	REP	0.25	0.05	2.8	1.63
			MJR	0.35	0.06	1.5	4.28
			MNR	0.40	0.07	0.8	8.91
Water utility Assets	Pipes	0.34	REP	0.26	0.09	14.4	0.61
			MJR	0.35	0.12	10.8	1.09
			MNR	0.39	0.13	7.2	1.82
	Fittings	0.32	REP	0.26	0.08	4.8	1.73
			MJR	0.35	0.11	3.6	3.10
			MNR	0.39	0.12	2.4	5.19
	Air valve	0.18	REP	0.05	0.01	3.6	0.25
			MJR	0.15	0.03	2.8	0.95
			MNR	0.80	0.14	2.0	7.11
	Water meters	0.17	REP	0.10	0.02	30.0	0.06
			MJR	0.70	0.12	22.5	0.52
			MNR	0.25	0.04	15.0	0.28

Figures 9 and 10 show the trade-off analysis for the road assets and water pipe assets, respectively. It should be noted that C_{pqrs} denotes these 81 maintenance alternatives from C_{1111} to C_{3333} as defined in the research methodology (section 3.6). When more than one intervention alternative satisfies the budget constraints, the asset manager can select the optimum intervention alternative by considering the WP/cost value. This will result in a solution with the maximum benefit/cost value. For instance, assume a constrained budget of LKR 40 Mn (USD Mn 0.12), each available for roads and water pipes. There are three maintenance alternatives for roads (C_{2111}, $C_{2121,}$ and C_{2211}) that will record total cost values of LKR 34.4 Mn, 33.3 Mn, and 33.3 Mn, respectively. As the maintenance cost for all these alternatives is closer to LKR 40 Mn (USD Mn 0.12), their relative WP/cost value can be considered to identify the optimum intervention alternative. The WP/cost values for the alternatives C_{2111}, $C_{2121,}$ and C_{2211} are 4.89%, 5.8%, and 6.35%, respectively. Therefore, considering both cost and priority, the optimum intervention for road assets could be selected as the C_{2211} (pavements = REG+ RSF, structures = MJR, corridor items = REP, and traffic facilities = REP). Similarly, for a pipe network with a constrained budget of LKR 40 Mn (USD Mn 0.12), intervention alternative C_{2232} (pipes = MJR, fittings = MJR, air valves = MNR, and water meters = MJR) with a total cost of LKR 38.9 Mn and a WP/cost of 11.82% could be selected as the optimum intervention alternative. A similar approach has been used by previous researchers [48, 49] to perform the trade-off analysis of roads and bridges when constrained budgets are imposed for maintenance. According to Amador-Jimenez and Mohammadi [38] adhering to a trade-off analysis method has generated an 8.83% saving in a road and utility pipe asset integrated management system in Canada compared to the isolate maintenance (silo) approach.

Accordingly, the option that satisfies the budget limit and provides the highest benefit (highest improvement in the asset system) should be given the highest priority in maintenance. This approach of asset maintenance can be used by asset managers to gain maximum improvement in all assets when the available budget for maintenance of a particular project is limited. This ensures all elements in the asset system are upgraded to some extent which delays the total failure of the system until the funds are available to bring all assets to near-perfect condition.

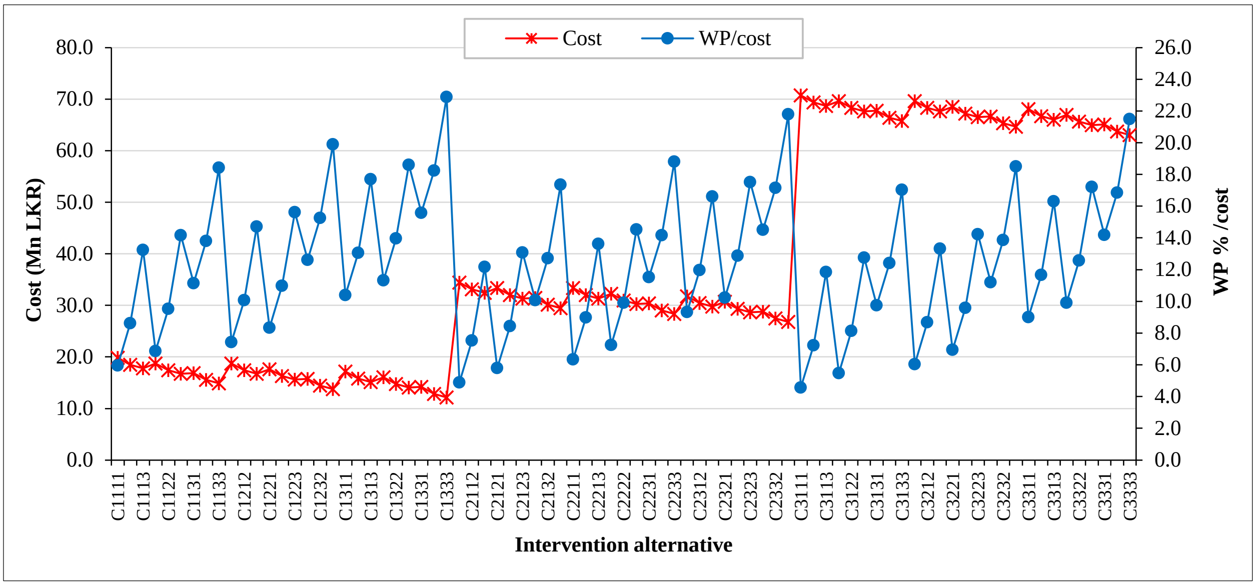

Figure 9. Trade-off analysis for road assets

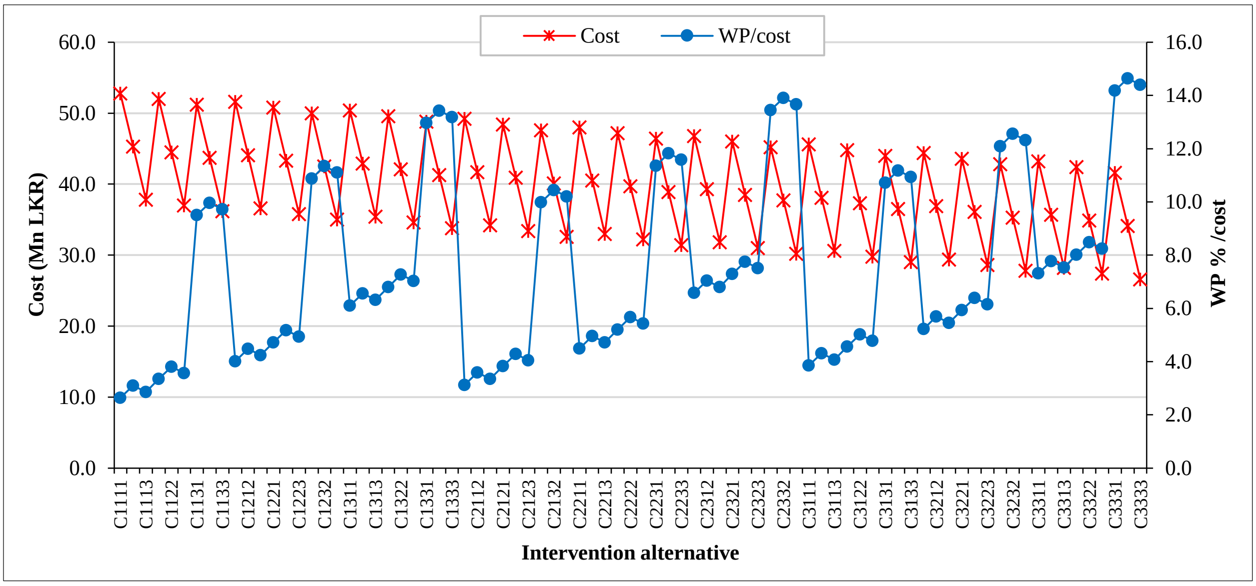

Figure 10. Trade-off analysis for water pipe assets

6. Conclusions

This study investigated an optimum fund allocation model using the analytic hierarchy process (AHP) for an asset system consisting of road assets and water pipe assets. The AHP was developed based on the opinions of 40 asset maintenance experts collected through two questionnaires on road asset maintenance and water pipe asset maintenance. Key criteria, maintenance options, and critical asset elements for maintenance were identified through these questionnaires, and the final maintenance priorities for the two assets were developed and combined to obtain the overall asset system maintenance priorities. The following conclusions are drawn based on the findings from this study:

- Safety, hazard mitigation, and the condition of the infrastructure are common criteria for road and water pipe assets for asset maintenance. Safety and condition of the pipe network were identified as the criteria with the highest weights in the road asset and water pipe asset, respectively, while environment conditions/mobility and the agency cost were found to be the criteria with the lowest weights in the road asset and water pipe asset, respectively. These differences in the criteria weights depict that road assets are more biased towards safety and available funds, whereas water pipe assets are more biased towards uninterrupted service.

- Road pavement and water pipe segments were identified as the critical asset elements for road and water pipe assets based on relative priority values. These two elements act as the main serviceable elements in the asset groups and commonly decide the condition of the entire network. In addition, they occupy the largest extent in the asset group and therefore require the highest maintenance costs due to high failure rates. Road asset managers prefer to perform preventive maintenance activities (resurfacing - RSF) on pavements very frequently, as this is a low-cost maintenance treatment option compared to other alternatives. The least preferred maintenance option in the road asset group is rehabilitation (RHB), which requires the highest funding and other resources. In contrast, the optimal maintenance option for the water pipe is selected as a replacement (REP) at the end of its service life, although this option incurs higher costs compared with other maintenance options. This is because the pipe maintenance requires the demolition of the road corridor, incurring high costs, and therefore, the asset managers do not prefer frequent minor maintenance activities. Due to the same reasons, the least preferred maintenance option for water pipes is frequent minor repairs (MNR).
- When the maintenance budget is constrained by 40%, the budget allocation for the water pipe asset group showed a decrease by 3.39%% in the fund allocation compared to the unconstrained budget, whereas the road assets showed an increase in the fund allocation by 5.09% in the constrained budget compared to the unconstrained budget allocation. The constrained budget allocation percentages have increased for all road asset elements except traffic facilities, while budget allocations for all pipe asset elements have decreased. These changes are decided based on asset element priority, the extent of the asset group in the considered road corridor, and the maintenance unit cost values.
- The outcome of the conducted case study revealed that the intervention combination that satisfies the budget limit while yielding the maximum benefit/cost should be selected as the optimum maintenance option. For instance, for a limited budget of LKR 40 Mn (USD Mn 0.12) for each asset, the optimum maintenance options for the four critical asset elements in the road asset are ‘regulation + resurfacing (REG+RSF) for pavements, major repair (MJR) for structures, and replacement (REP) for both corridor items and traffic facilities. Similarly, the optimum intervention options for the four critical asset elements in the water pipe assets are major maintenance (MJR) for pipes, fittings, and water meters and MNR for air valves. It should be noted here that these optimum intervention options are decided based on both the available budget and the priority of the asset elements. Hence, this can be highly case-dependent, and decision-makers should select the maintenance option based on their goals, available resources, and budget.
- The methodology demonstrated in the case study could be used to prioritize the fund allocation for multiple assets related to a maintenance project when the budget is constrained. This methodology can be adapted to a wide range of applications by changing the criteria, priority weights, and maintenance options.
- The optimization based on AHP is highly subjective based on local practices. Therefore, the best management strategy for cross-asset maintenance should be decided based on the local practices in each country. However, the method outlined in this study will serve as a guideline to develop a cross-asset fund allocation model when more than one asset group is involved in the maintenance. Also, the proposed methodology can be extended for the integration of multiple infrastructure asset groups to come up with an optimum fund allocation strategy.

7. Declarations

7.1. Author Contributions

Conceptualization, J.A.N.N.J., M.C.M.N., and D.J.R.; methodology, J.A.N.N.J.; data collection and analysis, J.A.N.N.J.; resources, M.C.M.N., S.K.N., and L.C.K., writing—original draft preparation, J.A.N.N.J.; writing—review and editing, M.C.M.N. and D.J.R.; supervision, F.G. and C.G.; project administration, D.J.R.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data sharing is not applicable to this article.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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