A FRAMEWORK OF GIS-BASED DECISION SUPPORT SYSTEM FOR HIGHWAY PAVEMENT MAINTENANCE MANAGEMENT AT THE NETWORK LEVEL

JUNDA LI, MICHAEL PITT and LING MA

The Bartlett School of Sustainable Construction, University College London, London WC1E 6BT, the United Kingdom

ABSTRACT

With the ever-increasing scale of highway networks in many countries, highway agencies need to improve their decision-making in highway pavement maintenance management (HPMM) to be more efficient, rational, and effective. This paper presents a framework of a GIS-based HPMM system. The input data, system architecture, main functions, key technologies, and data model design to establish the system are discussed. Four decision support models that can address a wide range of problems in HPMM are integrated into this system, including: (1) pavement performance evaluation based on inspection data; (2) predicting pavement performance development based on historical pavement condition data; (3) formulating optimal maintenance plan using multi-objective heuristic; (4) prioritising pavement sections in the highway network for maintenance considering multiple factors through MCDM approach. The system will be developed based on commercially available ArcGIS platform. GIS provides various tools for spatial analysis, linear referencing, and dynamic segmentation, enabling these decision support models to be applied more reliably and efficiently, as well as dynamic visualisation and interpretation of the attributes and output results.

Keywords: pavement management, pavement maintenance, decision support system, GIS.

INTRODUCTION

With the ever-increasing scale of highway pavement networks worldwide, a new problem has appeared for highway agencies in many countries: the maintenance of their ageing pavement networks (Wang et al., 2021). Compared with the design and construction phases, the operation and maintenance phase of a highway project lasts tens of years, in which many surface distresses emerge because of complex factors, e.g., increasing and repeated loadings, climate variation, and geological conditions (Kumar and Suman, 2022). Therefore, highway agencies spend large amounts of funds yearly for pavement maintenance activities to maintain their highway network serviceable.

Currently, the decision-making of highway pavement maintenance management (HPMM) is based on experts' experience and knowledge, which is subjective, time-consuming, error-prone, and cannot meet the requirements of maintaining large-scale highway pavement networks. Therefore, highway agencies need to improve their decision-making in HPMM to be more efficient, reasonable, and reliable (Abu Dabous et al., 2020). Consequently, the highway maintenance decision support system came into being with various models integrated into its framework, which can provide effective solutions for issues in HPMM.

Geographic Information System (GIS) is a system that creates, manages, analyses, and maps geospatial data, which can offer some specific functions that can promote the approaches of HPPM (Oswald Beiler and Treat, 2015). The key feature distinguishing GIS from other data systems is how geospatial data are stored and processed. The spatial dimension is the source of the power of GIS (Nautiyal and Sharma, 2021). Many studies have reported that many factors should be considered in the decision-making process of HPMM, including pavement performance indices, economic factors, such as maintenance costs, environmental factors, such as climatic and geological conditions, and social factors, such as benefited population, critical infrastructures nearby, and presence of alternative road (Godoy et al., 2015, Abu Dabous et al., 2020, Dessouky et al., 2016, Gutekunst et al., 2016). Many of these factors are spatially distributed along the highway route, and so are well suited to GIS analysis, which has the potential to improve the decision-making process of HPMM regarding efficiency, money, and the effectiveness of decisions.

This paper developed a framework to establish a GIS-based decision-support system, which considers multiple factors and includes several important decision support models that support HPMM. The paper is divided into five sections, starting with an introduction to the research problem. The second section addresses the establishment of the system structure and main functions. A discussion of key technologies that will be used in the system is presented in the third section, followed by a discussion of the data model design in accordance with the application requirements of the system, and finally, the study is concluded in the fourth section.

SYSTEM ARCHITECTURE AND MAIN FUNCTIONS

The architecture of the system is shown in Fig. 1, of which the main functions include data maintenance, GIS, data analysis, decision support, etc.

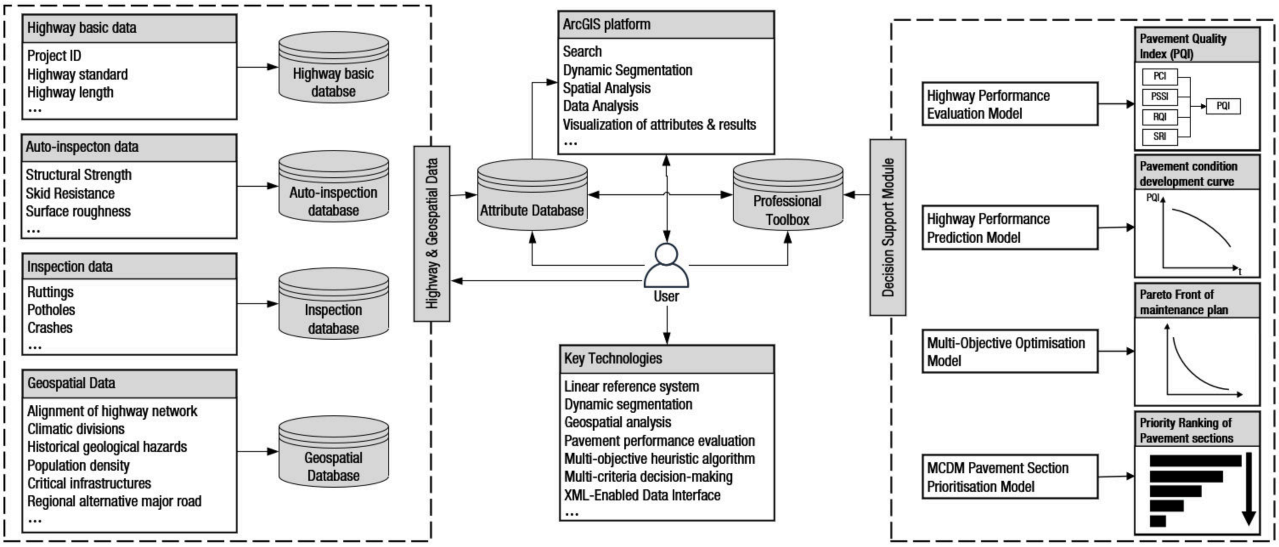

Fig. 1. System architecture of the HPMM decision support system

Data Collection

The data needed in the system includes geospatial data, basic highway data, highway condition data, traffic data, etc. Geospatial data include vector data and raster data of spatial-related factors in the area of the highway network, which are processed in ArcGIS platform (ESRI, 2022a). Types of geospatial data are shown in Table 1. The route data of the highway network and the alternative road can be obtained from the digital map owned by the highway agency or field survey. Other geospatial data are used to quantify the environmental, and social factors considered in the decision-making of maintenance management. These data can be extracted from the websites of some open access databases, e.g., ArcGIS hub (ESRI, 2022b). The highway basic data include the project ID, length, standard, etc. The pavement condition data include values of several pavement performance indices, including pavement defects (e.g., cracking, rutting, and potholes), Pavement Condition Index (PCI), Ride Quality Index (RQI), Pavement Structural Strength Index (PSSI), Skid Resistance Index (SRI), and Rutting Depth Index (RDI) (Gong et al., 2021, Kayadelen et al., 2022, Kumar and Suman, 2022, Shi et al., 2018), and can be obtained in an integrated manner of automated equipment collection and regular manual inspection, while traffic data can be extracted from the system of operation department in the highway agency.

Table 1. Types of geospatial data

Data	Type of data
Alignment of highway network	Polyline data
Climatic divisions	Polygon data
Geological hazards	Point data
Population density	Raster data
Critical infrastructures	Point data
Regional alternative major road	Polyline data

Data Maintenance

The objects of data maintenance include geospatial database, highway basic database, highway inspection database, etc. The maintenance of geospatial and attribute databases includes editing geospatial data, adding geographic attributes, etc. Basic data of highway network is stored in the basic database, which is static; Routine inspection records, pavement defects data, etc., are stored in the inspection database, which constantly changes over time. Decision support model base stores decision support models that are applied in the decision support module and the set parameters within those models. The data is input into the system in a combined way of manually direct input and batch input. The system will also provide routine functions such as data editing and modification, data backup, and recovery.

GIS

GIS offers an integration platform of highway data to manage the spatial-related data, which provides the functions of query of geospatial attribute data and spatial analysis and can visualise the output results of decision support module, including the evaluation results of highway condition, prediction of highway condition development, formulation of the highway maintenance plan and priority ranking of highway sections for maintenance activities.

Decision Support

This module is the core module of the system and provides functions that include evaluation of pavement conditions based on the inspection data, prediction of pavement performance development based on historical pavement condition data, formulation of highway pavement maintenance plan over an analysis period constraint to available budget and technical requirement based on multi-objective optimisation approach, and prioritisation of pavement sections for maintenance in the network based on MCDM approach. These models are integrated into the system with a data interface connected to the toolbox, giving easy access for customisation, and optimisation of model parameters.

Pure decision support models are rarely used in practical pavement maintenance analysis because the input parameters in these models sometimes fail to reflect the real engineering conditions. The system adopts a combined manner that includes both automated and expert decision-making. The system can first automatically generate the decisions for some specific problems based on the decision support models for highway managers, which will be evaluated by these managers with their knowledge and experience. The system can then train the maintenance decision support model according to the evaluation results, adjust the model parameters to constantly improve the model and finally provide the optimal maintenance plan. The workflow of the decision-making process of this system is shown in Fig. 2.

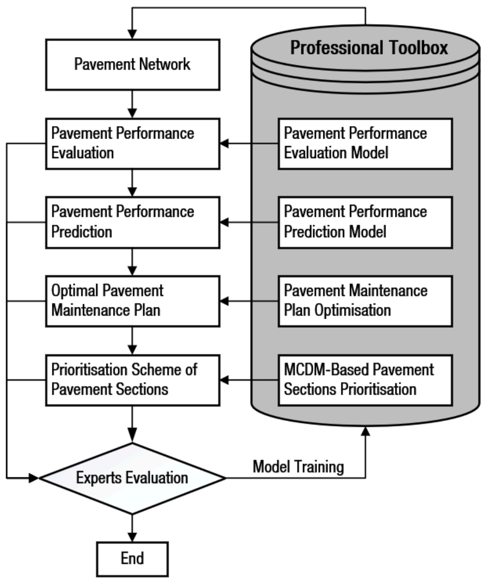

Fig. 2. Workflow of decision support module in the system

KEY TECHNOLOGIES

Linear Reference System (LRS)

In the GIS, geographic data can be modelled in several ways, that is, vector data, raster data, and triangulated irregular network (TIN) format (Huang et al., 2008). Data that have a discrete location with a defined shape and boundary is modelled as vector data. Such type of data is represented by features, which are stored in feature classes. Every feature has a geometry associated with it, which is composed of two-dimensional (x,y) or three-dimensional (x,y,z) geographic coordinates. The (x,y) or (x,y,z) coordinate systems can work well for modelling features with static characteristics, for instance, buildings, and lakes. However, in some other applications, such as highways, modelling the relative location along linear features would be more effective. These systems use a relative location along an existing linear feature to record data. In other words, location is defined with a known linear feature and a measure along it. For instance, route 01, 10.2 kilometres, can uniquely identify an accident in geographic space more intuitive than two-dimensional coordinates, as shown in Fig. 3.

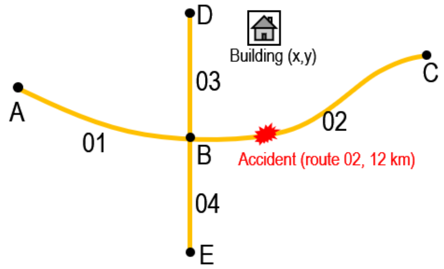

Fig. 3. Linearly referenced traffic accident

The linear reference system includes the linear referencing method, linear network, and linear event (Huang et al., 2008). The linear referencing method is used to locate the linear event in a linear network, which provides a way to measure along some type of linear feature. Linear events include point and line events. The former includes different pavement defects, such as rutting, potholes, and cracking, and the latter includes the average roughness of a pavement section, the PCI values, etc.

Other than making position information more intuitive, referencing a relative position along a highway can guarantee events that occur along the road being mapped as such. Conversely, locating events using two-dimensional coordinates may lead to events not falling along the road network in the absence of an accurate base-map.

A linear feature normally has only one set of attributes. However, with the linear reference system, it is possible to express unknown linear features directly through the position data of known linear features and the relative position relationship between each other without the two-dimensional coordinates. Therefore, the amount of required geospatial data decreases remarkably, which makes data more convenient to store, maintain, and query. Overall, with the linear reference system, the process of understanding, maintaining, and analysing linear features in the GIS can be greatly improved.

When linearly referenced features are referred to in this thesis, terms such as route and route events are used.

Route: A route is a type of linear feature that can be used to locate route events. It is characterised by a measurement system that includes a starting value and other values along the route (Curtin, 2007), which are used to position the attributes, also known as events, on the route. A route is different from a normal polyline in terms of measure values.

Event: An event is an attribute that is used to describe a portion or a single location of the route (Fischer, 2006). This portion and single location are referred to as the line and point events, respectively. Once a route has been defined (that is, spatial location, direction, and measure value), event data can be transferred on the route via dynamic segmentation (Jelokhani-Niaraki et al., 2010).

Line event tables should contain more than one measure indicating the location of the line event along the route, as well as a route identifier to indicate which route the event corresponds to (Jelokhani-Niaraki et al., 2009). An example of a line event table containing pavement condition data is shown in Table 2. In this table, the line events are linked to routes via the “Route_ID” field, and the locations of the events on the routes are indicated by the “From_measure” and “To_measure” fields. Fig. 4 depicts stored PCI values of different pavement sections of the three routes in line event table.

Table 2. Line event table containing event data on PCI values

Route ID	From_measure (km)	To_measure (km)	PCI value
01	0	1.5	87.7
01	1.5	4.0	85.1
02	0	2.0	77.6
02	2.0	5.0	94.5
02	5.0	6.0	88.6
03	0	1.0	95.3
03	1.0	4.0	84.5

A point event is an event that occurs at a specific point location on the route, which can be referenced with a single measure value along the route (Curtin, 2007). Therefore, the point event table must include at least one field for measure location and a route identifier for the application of dynamic segmentation. Table 3 shows a point event table that contains information on pavement defects at specific points, and Fig. 4 displays those defects as point events on the routes.

Table 3. Point event table containing event data on pavement defects

Route ID	Measure (km)	Pavement defects
01	0.4	Rutting
01	2.3	Pothole
01	3.7	Cracking
02	1.3	Pothole
02	1.9	Cracking
02	3.4	Rutting
02	4.3	Pothole
03	0.6	Corrugation
03	1.5	Cracking
03	3.1	Rutting

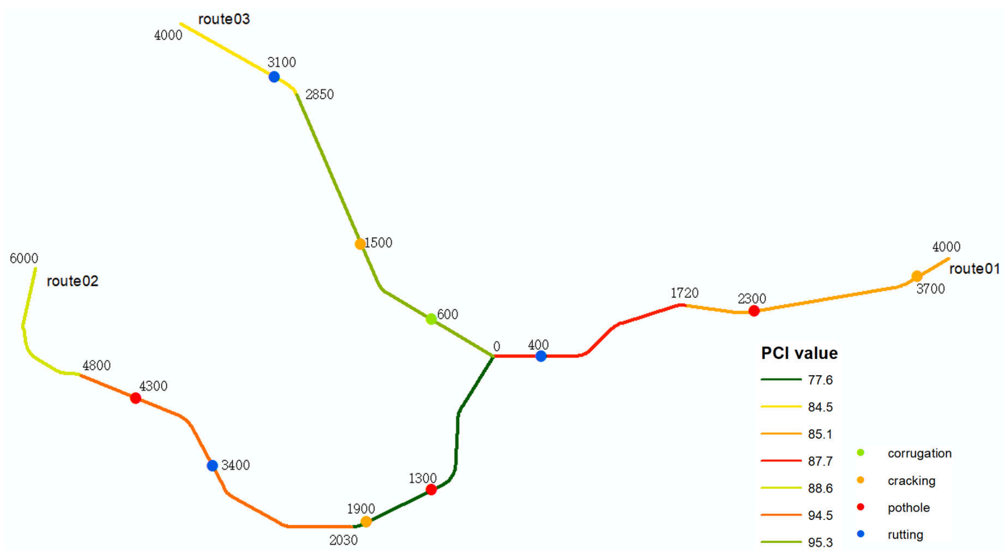

Fig. 4. Line and point events and measure locations on routes

Dynamic Segmentation

Dynamic segmentation, proposed by Fletcher in 1987, is a commonly used technique in the G-PMS to manage heterogeneous attributes along pavement networks, where sections and links have multiple-to-one relations (Zhou et al., 2000). Dynamic segmentation involves the segmentation of pavement networks into sections for given attributes. The segmentation is dynamic because it responds to changes in the network attributes, creating new segments accordingly by segmenting the linear feature into a new set of sections (Gupta et al., 2003). With dynamic segmentation, information initially gathered in a table can be visualised, queried, and analysed in a GIS platform. It can be considered an technique that is able to deal with dynamically and continuously changing attributes and defines multiple overlappings of route sections, which can help users avoid excessive and uncoordinated segmentation (Guo and Kurt, 2004). Dynamic segmentation also computes coordinates from linear references in a real-time manner to avoid the requirement of clear expression for all point features and segment boundaries in the geodatabase (Vonderohe et al., 1993).

The steps involved in applying them to update point and line events in the system include the following: First, based on the digital maps, a highway route can be established with linear features in the GIS platform, which acts as a reference line for the highway events. Then, point and line event tables can be established based on the highway pavement information. Finally, a new route attribute table can be created according to the jumping-off and end points of multiple attributes. This process is essentially conducted by overlaying and dissolving event tables to produce a new route attribute table, and after the establishment of attribute tables, various event/attribute information can be queried, searched, analysed, and displayed on a new feature layer in the GIS. Fig. 5 is the resultant diagram of the unification of the two attributes PCI and SRI, based on dynamic segmentation in the ArcGIS platform, and Fig. 6 is the schematic diagram.

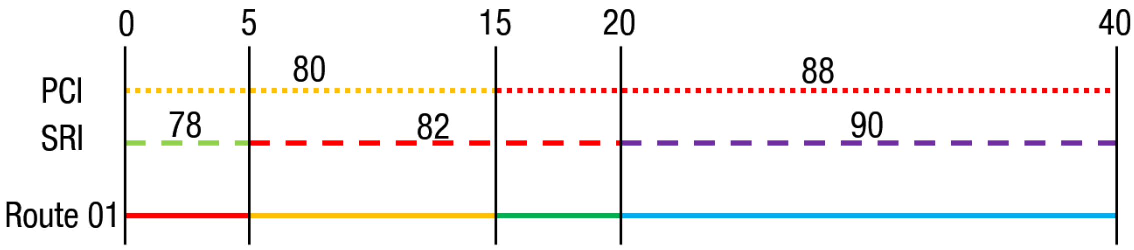

Fig. 5. Dynamic segmentation analysis between the PCI and SRI

Route_ID	From_Measure	To_Measure	PCI
01	0	15	80
01	15	40	88

Route_ID	From_Measure	To_Measure	SRI
01	0	5	78
01	5	20	82
01	20	40	90

Route_ID	From_Measure	To_Measure	PCI	SRI
01	0	5	80	78
01	5	15	80	82
01	15	20	88	82
01	20	40	88	90

Fig. 6. Schematic diagram of dynamic segmentation analysis between the PCI and SRI

As mentioned, dynamic segmentation has advantages to deal with linear features in the GIS, which can be a solution that provides several practical benefits over the arc-node model, including the following:

1: Better storage of attributes: In the arc-node model, attributes associated with linear features are defined using a single attribute table. This can cause problems if the linear features have many or dynamic attributes because the table can be too large, which can reduce the system capability (Jelokhani-Niaraki et al., 2009). Dynamic segmentation offers a more reasonable and efficient approach that stores each set of attributes separately in various event tables.

2: Improved accuracy of attribute values: In the arc-node structure, only one value of each attribute is associated with an arc, which is the averaged attribute values of all parts of the arc. This can be harmful for the accurate representation of attributes, especially when the arc is long. However, dynamic segmentation provides precise and high spatial resolution segments, which reduces the amount of space required for data storage while enabling more concentrated and precise data, leading to more careful queries (Singh and Dutta, 2006).

3: Flexible pavement management: By allowing for the segmentation of arcs without requiring split points or splitting lines into pieces, dynamic segmentation helps to decrease data redundancy by making the arc sensitive to attribute changes, which can significantly decrease the data amount, complexity of data storage, and network analysis in the system (Smadi et al., 1999).

4: Sharing network infrastructure: Dynamic segmentation allows for multiple organisations to use a single public base road network, leading to the sharing of network infrastructure across different applications and reducing the need for duplicated data.

5: Easier update and historical storage: Dynamic segmentation makes the update and historical storage of arcs easier to perform by manipulating event tables rather than the more complex operations required in the arc-node structure.

Overall, the use of dynamic segmentation can provide a more efficient and effective way of storing and managing linear features in the arc-node structure, leading to improved flexibility, accuracy, and data management.

Geospatial Analysis

Comprehensively analysing spatial-related factors is important for effective decision-making in HPMM. GIS provides a number of spatial analysis tools, e.g., Overlap, Union and Intersect, which enables spatial overlay, intersection and other analysis towards the highway sections that are divided based on dynamic segmentation with other geospatial factors, including polygon factors, point factors and raster factors, as shown in Fig. 7.

For polygon factors, such as climate, the Overlay tool can be applied to compute the mileage of highway sections in different climate areas, and thus climatic attribute values of different sections can be calculated.

For point factors, such as critical infrastructures in the network area, the Buffer Tool can be employed to establish a buffer for each pavement section with a defined affect distance. Next, the Join Tool can be employed to count the number of critical infrastructures covered by each buffer, which indicates the number of critical infrastructures within the accessible range of the corresponding pavement section.

For raster factors, such as population density, similar to point factors, the Buffer Tool should first be used to obtain the benefited area of each pavement section. Then, the Zonal Tool can be applied to obtain the benefited population of each section.

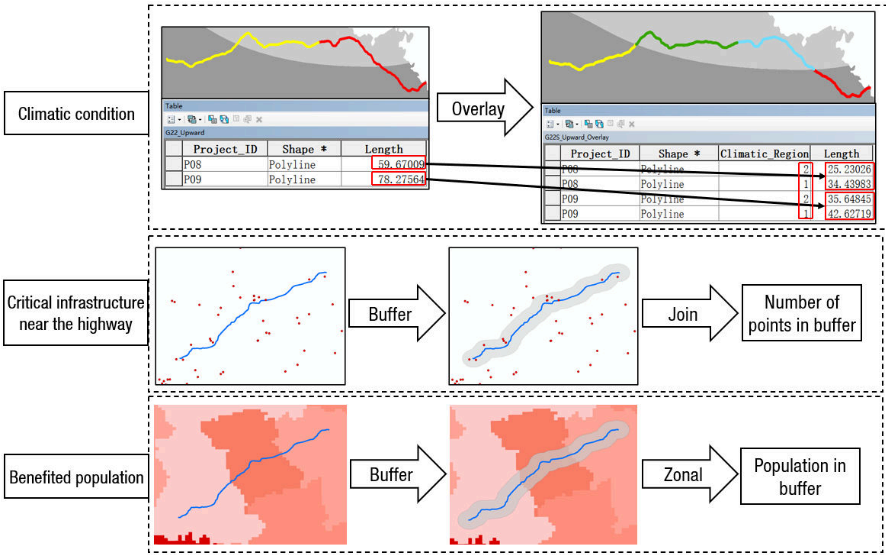

Fig. 7. Geospatial analysis in ArcGIS platform

Decision Support Models

Pavement Performance Evaluation

Pavement performance refers to its ability to serve traffic during a period of time. The functions of the highway should not only include bearing the repeated loadings of traffic flows but also meet the requirements of providing a high-speed, safe, and comfortable driving environment to the highway users within a certain design service life. Therefore, in a functional sense, pavement performance can be divided into structural performance and functional performance. At present, many highway agencies have preliminarily established pavement performance evaluation model (Cui, 2020), which evaluates the comprehensive performance of the pavement, denoted as Pavement Quality Index (PQI), according to the five indicators (PCI, RQI, RDI, SRI, and PSSI). As shown in Eq. (1).

$$\mathrm{PQI} = w_{\mathrm{PCI}}\mathrm{PCI} + w_{\mathrm{RDI}}\mathrm{RDI} + w_{\mathrm{SRI}}\mathrm{SRI} + w_{\mathrm{PSSI}}\mathrm{PSSI} \quad (1)$$

where w_{PCI}, w_{RQI}, w_{SRI} and w_{PSSI} refer to the weights of PCI, RQI, RDI, SRI, and PSSI in PQI.

Pavement Performance Prediction

Pavement performance prediction plays an important role in HPMM. To a certain extent, the accuracy of pavement performance prediction determines the reliability of the decision-making of the system because many decisions made by the system are based on the pavement performance development model, e.g., when and where to implement which maintenance treatment in the maintenance plan.

Many factors have an impact on the pavement deterioration rate, including pavement structure, traffic loading, climatic conditions, etc. Currently, there is no generic pavement performance prediction model, and models to predict pavement performance can be generally categorised into two types, i.e., deterministic and stochastic models (Shi, 2019). The deterministic prediction model takes the pavement performance as a single parameter to predict through regression analysis (Santos et al., 2017). Although environment and traffic conditions are not input into the model, their impacts are actually reflected in the historical values of pavement performance that are used for regression analysis. Stochastic models such as the reliability model, Markov decision model, Markov chain model, Bayesian model and hybrid stochastic model consider the impacts of environmental conditions, traffic loading, and other parameters that are uncertain to predict the pavement performance (Shi, 2019).

In the proposed system, the model proposed in Shi (2019) is used to develop the prediction model, of which the equation is shown as follows.

$$PQI = 100 - \frac{100}{1 + e^{\beta + k \times t}} \tag{2}$$

where t refers to pavement age (in year); β, k are constants, which are determined by regression analysis based on historical data.

Multi-Objective Optimisation Algorithm

To maintain the serviceability of the pavement, highway agencies should compare and analyse various feasible maintenance plans from multiple perspectives, e.g., technical and economic terms, to find the optimal solutions, so as to maximise the economic and social benefits with the limited budget (Guan et al., 2022). These analyses generally include: (1) Use the pavement performance evaluation model to evaluate the overall performance of the pavement network; (2) Estimate the maintenance requirements of all levels of pavement sections in terms of pavement performance based on the technical standard; (3) Analyse the minimum funds required to reach the required standard; (4) Use multi-objective optimisation model to optimise the allocation of maintenance funds in the highway network in a defined analysis period. Normally, highway agencies have multiple targets when making their maintenance plans, which often contradict each other, e.g., cost decrease may lead to worse pavement conditions. Therefore, it is nearly impossible to find a solution that is best regarding all considered objectives. In most cases, a set of solutions can be found, which cannot be further improved in any of the objectives without compromising the performance in another. The solution set in the solution space is defined as Pareto front (Afshari et al., 2019).

Multi-objective optimisation methods include mathematical and heuristic approaches. For a highway network consisting of S pavement sections, in an analysis period of T years, the form of the solution in the optimisation process can be defined as $P = \{p_{t,s}\}_{T \times S}$, as shown in Fig. 8. Each element $p_{t,s}$ in the matrix represents a treatment to be applied at the pavement section s in the year t. Theoretically, there are $M^{T \times S}$ solutions for the defined highway network if M maintenance treatments are available, which is a non-deterministic polynomial-time hard (NP-hard) problem (Santos et al., 2017). Therefore, for a large-scale highway network in service for tens of years, the problem can be very computationally expensive. Consequently, only heuristic approaches are able to solve such problems.

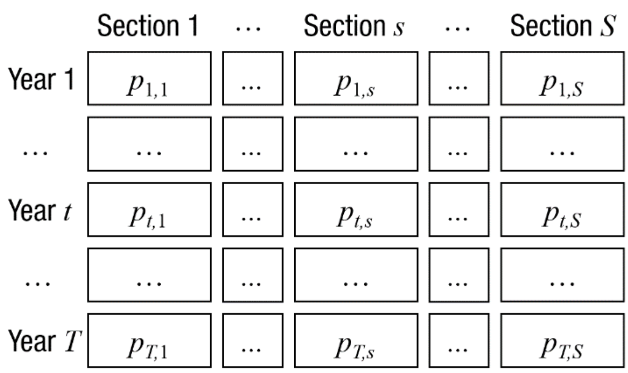

Fig. 8. The form of the solution

A novel developed multi-objective heuristic will be integrated into the system to automatically formulated the optimal maintenance plan. The following objectives should be considered: (1) minimising the life cycle agency costs of the maintenance plan; and (2) maximising the long-term pavement performance over the project life cycle. Therefore, the objective functions are:

$$\min F_1 = \min\left(\sum_{s=1}^{S} \sum_{t=1}^{T} (C_{p_{t,s}} \times W_s \times L_s)\right) \tag{3}$$

$$\max F_2 = \max\left(\sum_{s=1}^{S} \sum_{t=1}^{T} \left(\frac{PQI_{p_{t,s}} + PQI_{p_{t,s}}}{2} \times W_s \times L_s\right)\right) \tag{4}$$

where F_1 denotes the life cycle costs incurred by the highway agency, and F_2 denotes the long-term pavement performance of the highway network; $C_{t,x}$ denotes the cost of treatment $p_{t,s}$; $p_{t,s} = 1,\ldots, M$, each value of $p_{t,s}$ represents treatment type; $PQI_{t,x}$ refers to the PQI value of section s in year t under the analysed maintenance plan; W_s and L_s denote the width and length of pavement section s.

Finally, the optimisation model is subjective to several constraints, as shown in Eqs. (5)~(7). Processes of this optimisation is shown in Fig. 9.

$$s.t.\ \ LCAC \leq LCAC_{\max} \tag{5}$$

$$PQI_{p_{t,s}} \geq PQI_{\min} \tag{6}$$

$$PQI_{p_{t,s}} \in [UB_{p_{t,s}}, LB_{p_{t,s}}] \tag{7}$$

where $LCAC$ refers to the life cycle costs incurred by the highway agency for maintenance activities; $LCAC_{\max}$ denotes the defined budget; $PQI_{\min}$ is the minimal PQI value that should be guaranteed; $[UB_{p_{t,s}}, LB_{p_{t,s}}]$ is the application scope of the treatment $p_{t,s}$ in terms of pavement conditions.

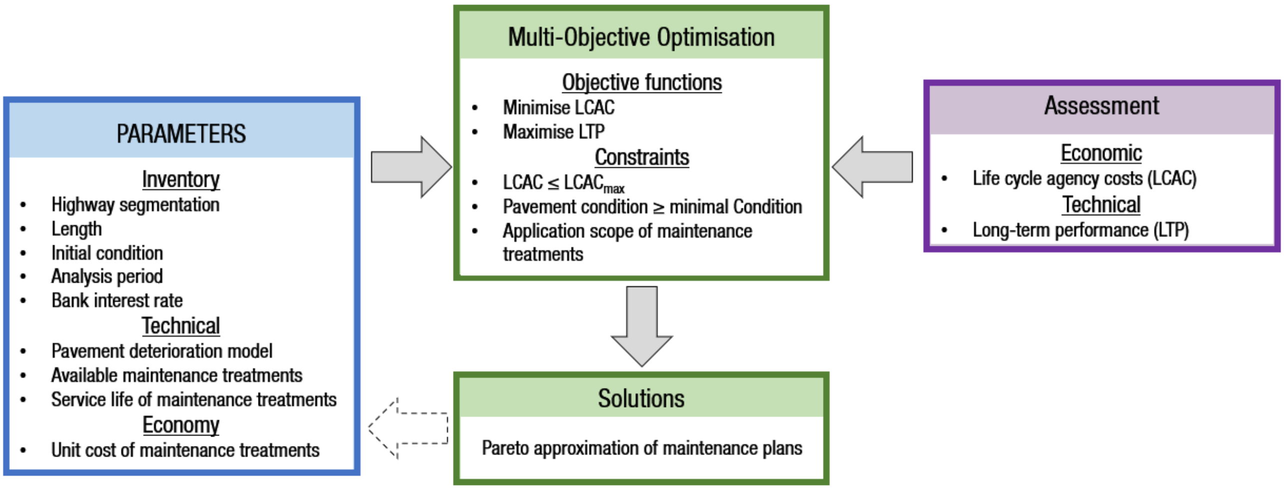

Fig. 9. Processes of the optimisation model for optimal maintenance plan

MCDM-Based Pavement Section Prioritisation for Maintenance

Although the maintenance plan can be formulated by the multi-objective optimisation model discussed in the last section, due to the uncertainties in constraints, e.g., work duration, available funds, and manpower, highway agencies may not be able to implement all the maintenance interventions on time according to the optimal maintenance plan. Therefore, a prioritisation scheme is needed to rank the priority of pavement sections in the network for maintenance activities (Nautiyal and Sharma, 2021).

Multiple factors should be considered when prioritising pavement sections in the highway network. Those factors can include pavement performance indices, environmental factors, and social factors. Since many factors are considered, MCDM can be an effective way to prioritise pavement sections, which is a powerful approach to evaluating multiple factors in terms of relative importance and objectives (Kumar and Suman, 2022). The application of MCDM approaches needs the quantification of decision factors considered. In the system, many factors that influence the maintenance priority of pavement sections can be quantified by spatial analysis tools in GIS, which paves the way to apply MCDM.

Most commonly used MCDM methods are based on the principle that the decision makers are totally rational, and their psychological preferences in the decision-making process are not taken into account (Zhang et al., 2022). However, the scenario might be different in pavement management as decision makers usually have risk-averse psychology due to the fact that maintenance interventions do not produce direct benefits, which, nevertheless can be costly, and the highway agency often only has limited funds. TODIM method is well-suited for this situation, which can accommodate considered factors accordingly to the decision maker's psychological preferences (Wu et al., 2018). Fig. 10 demonstrates an example of priority scores of different pavement sections in a network obtained by TODIM based on spatial factors processed by GIS.

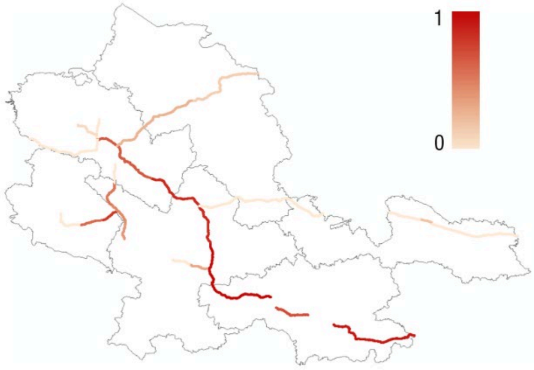

Fig. 10. Priority scores output by a GIS-TODIM model

HIGHWAY PAVEMENT DATA MODEL DESIGN

The successful application of the GIS highly depends on how data are structured or modelled. A data model represents the data and associated attributes, relationships, and a series of rules, which can be any structured set of data, relations, or data representation (Curtin et al., 2003). In this study, with the reorganisation of strengths of the dynamic segmentation, it is employed as the major foundation in the pavement maintenance data model to represent pavement maintenance information. Pavement maintenance data modelling includes conceptual, logical, and physical levels (Jelokhani-Niaraki et al., 2009).

Conceptual Model

At the conceptual level, a data model represents real-world phenomena in an abstract manner (Vonderohe et al., 1993). The output of conceptual data modelling is a conceptual schema, which is a diagram that captures the desired perspectives of reality at a high level of abstraction using the notation or grammar of the selected conceptual data model (Tryfona and Jensen, 1998). The conceptual data model presents the information structure, independent of implementation details, including the types of data and their interrelationships (Heo, 2001). The entity relationship diagram in Fig. 11 shows the proposed conceptual pavement maintenance data model. As demonstrated, this model includes four types of entities. The black entities present the structure of the pavement network, green entities represent non-highway objects, blue entities represent various line events, and purple entities represent point events.

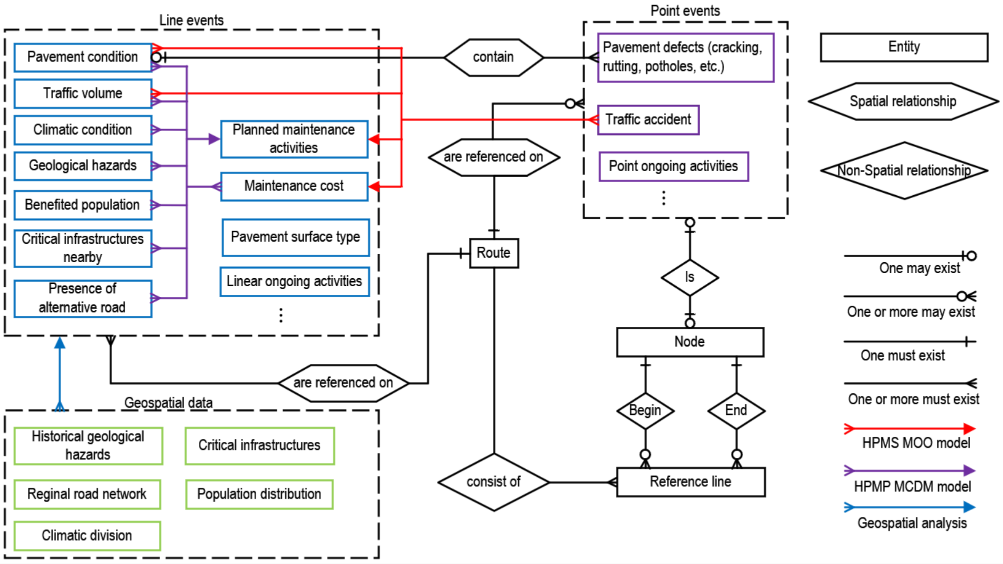

Fig. 11. Conceptual pavement maintenance data model

Logical and Physical Models

The purpose of logical data modelling is to translate the conceptual data model into a series of constructs within a database management system (DBMS). An object-relational model structure is adopted in this process, in which the relational model is extended and integrated with the object-oriented concept, thus taking advantage of both the relational and object-oriented models, providing more flexibility and functionality in data management (Zeiler, 1999, Jelokhani-Niaraki et al., 2009). The proposed logical model is designed based on the unified modelling language (UML) (Booch, 2005). The ArcGIS platform offers the functionality that can convert the UML logical model to an object-relational model, namely, a geodatabase (Butler, 2008). Meanwhile, the ArcGIS platform further provides a set of computer-aided software engineering (CASE) tools that enable users to design and establish geodatabases efficiently (Jelokhani-Niaraki et al., 2009), which use the UML to establish elements that represent geodatabase components, such as feature datasets, feature classes, and tables (Arctur and Zeiler, 2004). These can then be used for pavement management functions or applications. Fig. 12 and Fig. 13 show logical pavement maintenance data models in UML notation. These models define objects with spatial reference and those without spatial reference, as well as the relationships between them. Objects without spatial reference correspond to various line and point event tables of pavement network attributes. Objects with spatial reference correspond to feature classes and raster, which include the reference line, point, polyline, and polygon classes and raster objects. As shown in Fig. 12 and Fig. 13, the characteristics, types of attributes, and parameters of the relationships among objects can be identified and coded by the logical pavement maintenance data model.

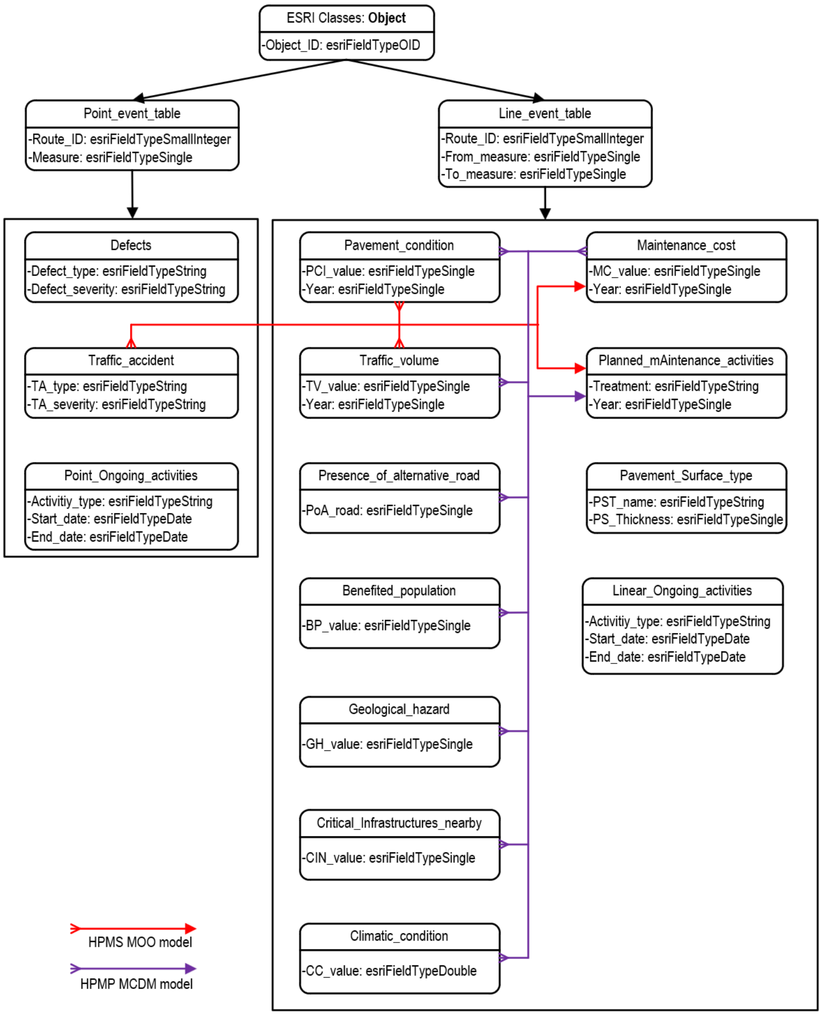

Fig. 12. Logical pavement maintenance data model of point and line events

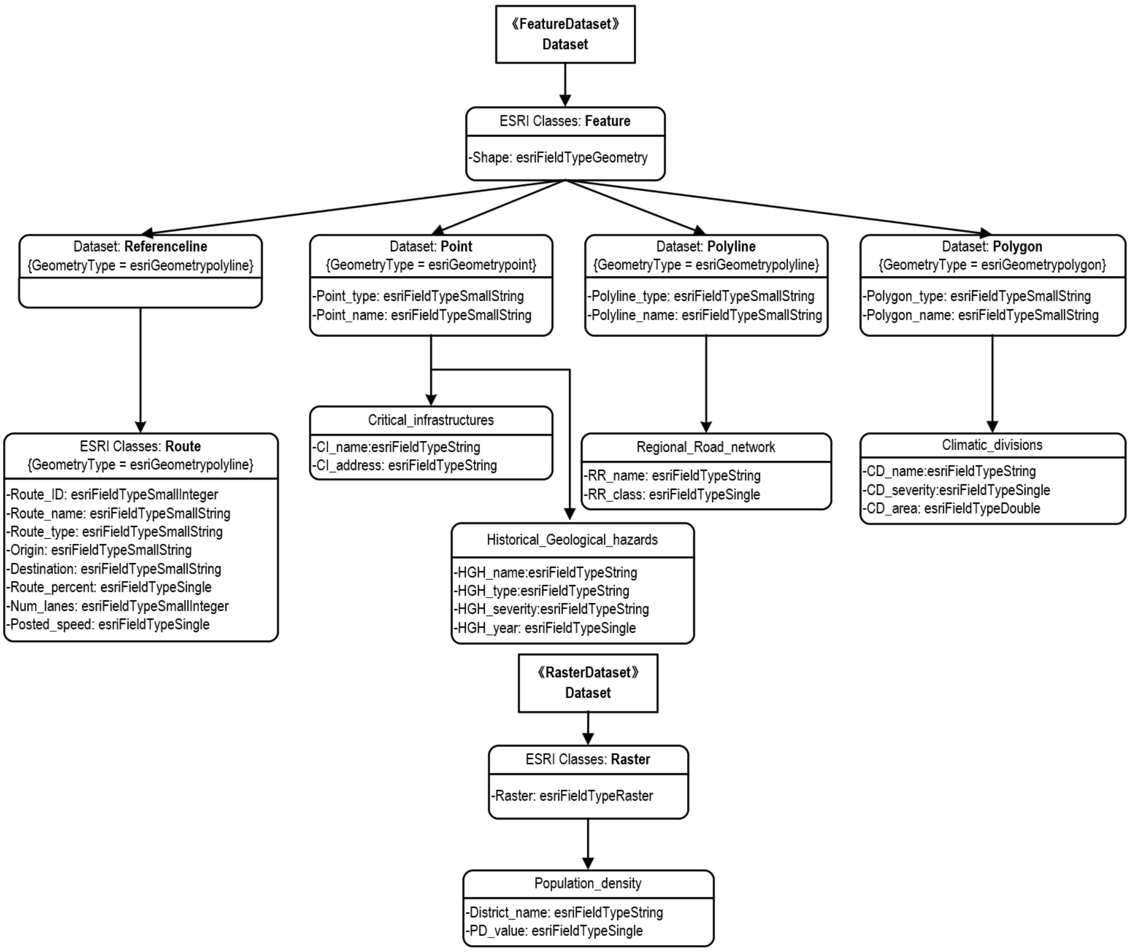

Fig. 13. Logical pavement maintenance data model of vector and raster entities

Finally, the physical level aims to obtain GIS databases from the established logical model, which implement the logical data model in a physical structure of the DBMS (Rigaux et al., 2002). As stated previously, objects of the logical model in the UML form can be easily transformed into the physical schema of feature classes, raster, and tables in geodatabase format using CASE tools, as shown in Fig. 14.

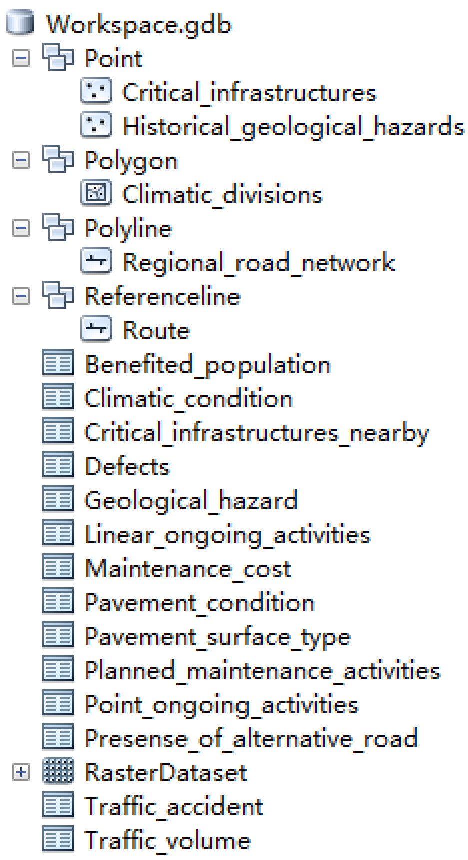

Fig. 14. Physical pavement maintenance data model

CONCLUSION

Decision-making in HPMM at the network level considering multiple factors can be challenging, especially when many spatial-related factors are involved. This process can be significantly promoted by applying GIS in terms of efficiency, cost and manpower, which provides powerful tools to store, analyse, manipulate, and visualise spatially distributed factors.

This paper presents a framework to establish a GIS-based HPMM decision support system. Several decision support models that can address a wide range of issues in HPMM are integrated into the system to apply them more efficiently, including: (1) pavement performance evaluation based on routine inspection data; (2) predicting pavement performance development based on historical data; (3) formulating optimal maintenance plan using multi-objective heuristic; (4) prioritising pavement sections in the highway network considering multiple factors through MCDM approach.

Based on LRS and DS in GIS, the proposed system can easily deal with the issues arising from linear measures of events on the highway routes and the uncertainty and dynamics within segmentation of pavement characteristics. The HPMM decision support system can enable the dynamic visualisation of pavement attributes and provide spatial analysis tools that can quantify the spatial-related factors efficiently, which are of great significance to the application of the integrated models.

This system can bridge the gap between geographic tools, multiple geospatial factors and decision support models. Reliability and reasonability can be achieved through the consideration of various decision factors. Decision support models integrated into the system improves the efficiency and effectiveness based on quantitative analysis. Finally, the integrated GIS platform serves as the database, professional toolbox, and a wide assortment of functions for HPMM.

REFERENCES

ABU DABOUS, S., ZEIADA, W., ZAYED, T. & AL-RUZOUQ, R. 2020. Sustainability-informed multi-criteria decision support framework for ranking and prioritization of pavement sections. *Journal of Cleaner Production,* 244.

AFSHARI, H., HARE, W. & TESFAMARIAM, S. 2019. Constrained multi-objective optimization algorithms: Review and comparison with application in reinforced concrete structures. *Applied Soft Computing,* 83.

ARCTUR, D. & ZEILER, M. 2004. *Designing Geodatabases: case studies in GIS data modeling*, ESRI, Inc.

BOOCH, G. 2005. *The unified modeling language user guide*, Pearson Education India.

BUTLER, J. A. 2008. *Designing geodatabases for transportation*, ESRI, Inc.

CUI, Y. 2020. *The Study on Maintenance Decisions of Expressway Network Asphalt Pavement Performance for Gansu Province.* Msc Thesis, Lanzhou Jiaotong University.

CURTIN, K., NORONHA, V., GOODCHILD, M. & GRISé, S. 2003. UNETRANS Data Model (Arc GIS transportation Data Model). Environmental Systems Research Institute Inc, Redlands, CA, USA.

CURTIN, K. M. 2007. Network Analysis in Geographic Information Science: Review, Assessment, and Projections. *Cartography and Geographic Information Science,* 34**,** 103-111.

DESSOUKY, S., PAPAGIANNAKIS, A. T. & ABBAS, A. 2016. Practical Tool for Prioritizing Rehabilitation and Preventive Maintenance in Pavements. *Transportation Research Record: Journal of the Transportation Research Board,* 2550**,** 63-71.

ESRI. 2022a. *ArcGIS Desktop* [Online]. Available: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview [Accessed 23rd July 2022].

ESRI. 2022b. *ArcGIS Hub* [Online]. Available: https://hub.arcgis.com/ [Accessed 29th, June 2022].

FISCHER, M. M. 2006. GIS and Network Analysis. *Spatial Analysis and GeoComputation: Selected Essays.* Berlin, Heidelberg: Springer Berlin Heidelberg.

GODOY, P., MOURGUES, C. & CHAMORRO, A. 2015. Incorporating socio-political criteria into the maintenance prioritization of Chilean urban pavement networks. *Transportation Research Part A: Policy and Practice,* 80**,** 151-162.

GONG, M., ZHANG, H., LIU, Z. & FU, X. 2021. Study on PQI standard for comprehensive maintenance of asphalt pavement based on full-cycle. *International Journal of Pavement Engineering***,** 1-14.

GUAN, J., YANG, X., YOU, L., DING, L. & CHENG, X. 2022. Multi-objective optimization for sustainable road network maintenance under traffic equilibrium: Incorporating costs and environmental impacts. *Journal of Cleaner Production,* 334.

GUO, B. & KURT, C. E. 2004. Towards temporal dynamic segmentation. *GeoInformatica,* 8**,** 265-283.

GUPTA, P., JAIN, N., SIKDAR, P. & KUMAR, K. Geographical information system in transportation planning. Map Asia Conference, 2003. Citeseer.

GUTEKUNST, J., MOTAMED, M., ALRASHIDAN, A. & MACHEMEHL, R. B. 2016. Pavement Maintenance Prioritization Tool for Effects of Hydraulic Fracturing. *Transportation Research Record: Journal of the Transportation Research Board,* 2580**,** 65-70.

HEO, J. 2001. *Development and Implementation of a Spatio-Temporal Data Model for Parcel-Based Land Information Systems.* The University of Wisconsin-Madison.

HUANG, L.-X., ZHANG, H.-Y., YANG, L.-B., DENG, M.-R. & PENG, H.-Z. 2008. Application of linear reference system and dynamic segmentation in the GIS-T. *Geoinformatics 2008 and Joint Conference on GIS and Built Environment: The Built Environment and Its Dynamics.*

JELOKHANI-NIARAKI, M. R., ALESHEIKH, A. A., ALIMOHAMMADI, A. & SADEGHI-NIARAKI, A. Designing road maintenance data model using dynamic segmentation technique. International Conference on Computational Science and Its Applications, 2009. Springer, 442-452.

JELOKHANI-NIARAKI, M. R., ALESHEIKH, A. A. & SADEGHI-NIARAKI, A. 2010. An efficient approach for historical storage and retrieval of segmented road data in Geographic Information System for Transportation. *Chinese Geographical Science,* 20**,** 236-242.

KAYADELEN, C., ÖNAL, Y., ALTAY, G., ÖZTüRK, M. & SERIN, S. 2022. Effects of maintenance, traffic and climate condition on International Roughness Index of flexible pavement. *International Journal of Pavement Engineering***,** 1-13.

KUMAR, R. & SUMAN, S. K. 2022. Prioritization of Flexible Pavement Sections for Maintenance Using Multi-criteria FAHP Integrated with Multi-attribute Utility Theory. *Process Integration and Optimization for Sustainability*.

NAUTIYAL, A. & SHARMA, S. 2021. Condition Based Maintenance Planning of low volume rural roads using GIS. *Journal of Cleaner Production,* 312.

OSWALD BEILER, M. R. & TREAT, C. 2015. Integrating GIS and AHP to Prioritize Transportation Infrastructure Using Sustainability Metrics. *Journal of Infrastructure Systems,* 21.

RIGAUX, P., SCHOLL, M. & VOISARD, A. 2002. *Spatial databases: with application to GIS*, Morgan Kaufmann.

SANTOS, J., FERREIRA, A. & FLINTSCH, G. 2017. A multi-objective optimization-based pavement management decision-support system for enhancing pavement sustainability. *Journal of Cleaner Production,* 164**,** 1380-1393.

SHI, J. 2019. *Research on Sustainable Development of National Trunk Highway Maintenance Management and Preventive Maintenance Technology Compatibility.* Ph.D thesis, South China University of Technology.

SHI, X., MUKHOPADHYAY, A. & ZOLLINGER, D. 2018. Sustainability assessment for portland cement concrete pavement containing reclaimed asphalt pavement aggregates. *Journal of Cleaner Production,* 192**,** 569-581.

SINGH, Y. & DUTTA, U. 2006. Dynamic segmentation, a tool for infrastructure development. *Geospatial Today,* 5**,** 28-30.

SMADI, O. G., HANS, Z. N. & MAZE, T. Iowa Pavement Management Program Database: Integration and Delivery. 78th Annual Meeting of the Transportation Research Board, Washington, DC, 1999. Citeseer, 10-20.

TRYFONA, N. & JENSEN, C. S. 1998. A Component-Based Conceptual Model for Spatiotemporal Design. Athens, Greece: Dept. of Electrical and Computer Engineering, National Technical University of Athens.

VONDEROHE, A. P., TRAVIS, L., SMITH, R. & TSAI, V. 1993. Adaptation of geographic information systems for transportation.

WANG, P., LIU, P., WANG, C., WANG, A., GUAN, H., LI, S. & XIA, X. 2021. Optimal dynamic investment allocation on construction of intelligent transportation infrastructure and road maintenance with environmental costs. *Journal of Cleaner Production,* 284.

WU, Y., ZHOU, J., HU, Y., LI, L. & SUN, X. 2018. A TODIM-Based Investment Decision Framework for Commercial Distributed PV Projects under the Energy Performance Contracting (EPC) Business Model: A Case in East-Central China. *Energies,* 11.

ZEILER, M. 1999. *Modeling our world: the ESRI guide to geodatabase design*, ESRI, Inc.

ZHANG, M., YAN, Q., LI, W., TANG, G. & LIN, H. 2022. Sustainability performance assessment of photovoltaic coupling storage charging stations with novel multi-criteria decision-making technique. *International Journal of Electrical Power & Energy Systems,* 142.

ZHOU, C., LU, F. & WAN, Q. 2000. A conceptual model for a feature-based virtual network. *GeoInformatica,* 4**,** 271-286.

Email contact: junda.li.19@ucl.ac.uk