Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2023 Volume 29 Issue 5: 439–462
https://doi.org/10.3846/jcem.2023.19031

SCIENTOMETRIC ANALYSIS OF PAVEMENT MAINTENANCE: A TWENTY-YEAR REVIEW

Ankang JI[1], Xiaolong XUE[2*], Xiaowei LUO[3], Yuna WANG[2], Hengqin WU[1,4]

[1]*Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, P. R. China*
[2]*School of Management, Guangzhou University, Guangzhou, P. R. China*
[3]*Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, P. R. China*
[4]*College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, P. R. China*

Received 6 April 2021; accepted 10 February 2023

Abstract. Pavement maintenance is widely thought to be critical for promoting sustainability, playing a pivotal role in sustainable and resilient transportation infrastructure for growth in economic development and improvements in social inclusion. It has attracted increasing attention from both academia and industry over the past 20 years. Although several literature reviews have been conducted, there is still a lack of systematic quantitative and visual investigation of the structure and evolution of knowledge in this field. To address this lack, reported here is a comprehensive and objective scientometric analysis to visualize the status quo of research areas regarding pavement maintenance. Focusing on 614 journal articles collected from the Web of Science for 2001–2020, key researchers within the field are identified, as are the key research institutions, key countries, and their interconnections, as well as keywords, evolution trends, key publications, and citation patterns, along with the extent to which these interact with each other in research networks. Based on the in-depth analysis, a knowledge roadmap is provided to inscribe how pavement maintenance-related research evolves over time, greatly contributing to the understanding of the underlying structure of pavement maintenance, and to highlight the identified current research challenges and future research trends, thus potentially benefiting the academic community and practice field on multiple themes of pavement maintenance. The results of this research are instructive, providing a broad overview and holistic thinking for researchers and practitioners with respect to pavement maintenance research, as well as facilitating further research and applications for both academia and industry in improving pavement maintenance for sustainability.

Keywords: pavement maintenance, literature review, scientometric analysis, CiteSpace, social network analysis.

Introduction

Pavement maintenance (PM) is considered to be a pivotal backbone of sustainable and resilient transportation infrastructure and receives considerable attention from both academia and industry (France-Mensah & O'Brien, 2019; Gosse et al., 2013; Yu et al., 2018). Damaged pavements are both unsafe and unsightly, the condition of which will continue to deteriorate if not promptly repaired, potentially resulting in major problems such as traffic accidents. Statistically, pavement conditions play a significant role in traffic accidents, accounting for approximately one-third of traffic fatalities (175,080 deaths on U.S. highways from 2013 to 2017) (TRIP, 2022). The most appropriate solution to prevent such problems is to address them immediately. PM is widely recognized as an effective way of maintaining or improving pavement performance for ensuring safety and extending service life. In China, the total length of roads open to traffic reached 5.2 million kilometers by the end of 2020 (Statista, 2021) and is estimated to reach 5.8 million kilometers by 2030 (Xinhua, 2013), raising difficult problems for managers. The prevalent problems in the maintenance and management of pavement are potentially encountered in countries all over the world. Driven by this adverse trend, an effective survey of PM developments is urgently needed to enable the understanding of the current status as a reference for PM.

The first 20 years of the 21st century have seen significant progress in PM, accompanied by growth in economic development and improvements in social inclusion

*Corresponding author. E-mail: *xlxue@gzhu.edu.cn*

(Khahro et al., 2020). In line with this, PM researchers and practitioners have made rapid progress by studying applications and methods for supporting sustainable PM with PM research becoming diverse as more emerging technologies are integrated into PM-related projects. For example, Giustozzi et al. (2012) developed a multi-attribute life cycle assessment (LCA) to assess the environmental impacts of PM activities, including the analyses of life cycle costs, performance, and environment, upon which PM management can be improved through the implementation of energy-efficient treatments and strategies. Abaza (2016) proposed a "back calculation" of discrete-time Markov models for predicting future pavement conditions by considering two main groups of pavement defects, achieving good results. Settari et al. (2015) studied the effects of the recycled asphalt pavement materials added to the rolled compacted concrete on the mechanical properties and durability for application in pavement maintenance. Jo and Ryu (2015), Zhang et al. (2018a), Inzerillo et al. (2018), and Bang et al. (2019) applied computer vision techniques to survey pavements automatically for maintenance, rehabilitation, and reconstruction strategies. However, although the existing literature showcases detailed analyses in certain research areas, its diverse and extensive nature could hide genuine limitations and gaps, such as not appreciating whether communication exists between different subfields within the field and what the overall mainstream research is. Therefore, the full scope of PM research must be reviewed to delineate the most significant body of knowledge of PM and drive research toward the most valuable and critical areas.

A literature review is regarded as an expedient way to understand a research area in-depth, and PM has been reviewed in that way previously. For example, Sultana et al. (2013) examined the maintenance performance of road infrastructure by contracting and provided a beneficial analysis for practical implementation in improving PM and its management, this study, however, does not provide an overview of PM, limiting itself to the performance of PM. Sarsam (2016) reviewed the basics and concepts of the PM management system and introduced its application and development, thereby helping to master the capabilities of the system as an aid to road maintenance, this analysis, nevertheless, suffers from the limitations of relying exclusively on manual reviews and fails to provide insights from an objective perspective. Similarly, Khahro et al. (2020) analyzed and reviewed the relevant literature focusing on PM management systems, their results indicate an increasing interest in PM management, while the potential for profound analysis still exists. Additionally, Sánchez-Silva et al. (2016) used a critical review to identify the main conceptual and theoretical principles of maintenance and then to describe different deterioration mechanisms and the criteria, variables, and models used to define optimum maintenance policies from both a conceptual and theoretical standpoint. That work offers support for developing better maintenance models, but without painting a clear progression. Accordingly, Pérez-Acebo et al. (2018) provided an overview of the pavement management literature from 2000 to 2013 with different perspectives, including countries, institutions, and authors, and identifies and analyzes future research trends, nonetheless, it cannot consistently provide updates on the progression of the domain research. Recently, Peraka and Biligiri (2020) reviewed the developments in pavement-condition data collection and processing (e.g., data collection procedures, analytical techniques, decision-making tools, and processing methods) and discussed the chronological development in data analysis, homogeneous sectioning for selecting maintenance strategies, and prioritization and optimization of maintenance strategies, this study, however, can be further enhanced by mapping the development path of the research areas with visualization for better knowledge capture. Admittedly, those insights provided by experts are valuable for discussing, interpreting, and understanding this complex subject. However, limited efforts have been made to outline and visualize the trends in PM research, and the previous literature reviews have been mostly traditional ones, namely manual, qualitative, and prone to bias and limitation in terms of the number of articles reviewed.

To address such limitations, reported herein is a scientometric review of the PM literature, the aim being an overall description of this research field, primarily adopting an interpretivist philosophical approach and inductive reasoning to generate new theories or knowledge by exploring "what", "why", and "how" questions. To achieve those aims, the CiteSpace science mapping tool was used to perform a visual bibliometric analysis of PM research for interpreting the knowledge of the PM field, upon which inductive reasoning was applied to carve out the PM research roadmap, including research gaps and future research directions. The findings are expected to (i) summarize PM knowledge over the past two decades for providing researchers and practitioners with an in-depth and comprehensive understanding of the underlying knowledge structure, current status, and research trends of the global PM field, and (ii) describe and visualize the paths for understanding, and capture systematically and thoroughly the hot topics through science mapping for promoting further studies in this field. Against the aforementioned backdrop, the present study involves the following: (i) conducting scientometric analysis to visualize the research status quo objectively, and exploring the knowledge base and domains associated with PM by using author analysis, spatial distribution analysis, keyword analysis, and document analysis; (ii) identifying how keywords in PM research evolve to guide future work; (iii) proposing a PM knowledge map. The present research provides an overview analysis of the PM-related literature as possible with its sample size, offers a quantitative summary of the current status of PM knowledge, and explores the areas of knowledge and hidden connections within the PM discipline based on an interpretivist philosophical approach and inductive reasoning for understanding in depth.

The remainder of this review is organized as follows. First, the methodology of the literature search is introduced, then the results of the scientometric analysis are presented, including a critical review of the cluster-analysis results to discuss the research themes. Next, the current research status of the PM field is discussed, along with future research trends. Finally, conclusions are drawn.

1. Research method

To achieve the objectives of this research, an in-depth scientometric analysis was performed on PM publications and their academic relationships. An overview of the research process is shown in Figure 1.

1.1. Data acquisition

Data acquisition is a crucial step that has a significant effect on subsequent scientific analysis. To obtain precise and robust analysis results, the Web of Science (WoS) database was selected as the core dataset to retrieve the academic literature, this being because it is the largest accessible academic database that can provide the most comprehensive and influential journal articles within the field of PM (El-adaway et al., 2019). After pre-analysis, the following retrieval code was used in the WoS core collection: "Topic" = (("pavement maintenance") OR ("road* maintenance")), where * denotes a fuzzy search. To extract the proper documents, the time span was seriously considered. Evidence suggests that studies lose relevance after almost 10 years with poor impact and inappropriate citation for subsequent studies (Wang, 2013). In light of this, the recent studies in PM may be inconsistent with the continuity of studies from two decades ago with the advances in the field of PM facilitated by rapid economic and social growth. As a result, the search time span of the documents was set as being from 1 January 2001 to 31 December 2020. Initially, 1725 documents were identified for further screening. In this research, only journal articles published in English were selected for analysis, this being because they are reputable and reliable sources that usually provide more-comprehensive and higher-quality information, whereas other types of publications, such as book reviews, editorials, and conference papers, are published in large numbers containing less valuable or useful information with little benefit to be gained by including them, adding extra complexity to the analysis (Butler & Visser, 2006). Also, the research scope obviously had to be relevant to the PM field for research content and scientific mapping purposes. After this screening, the data set comprised 614 journal articles in total.

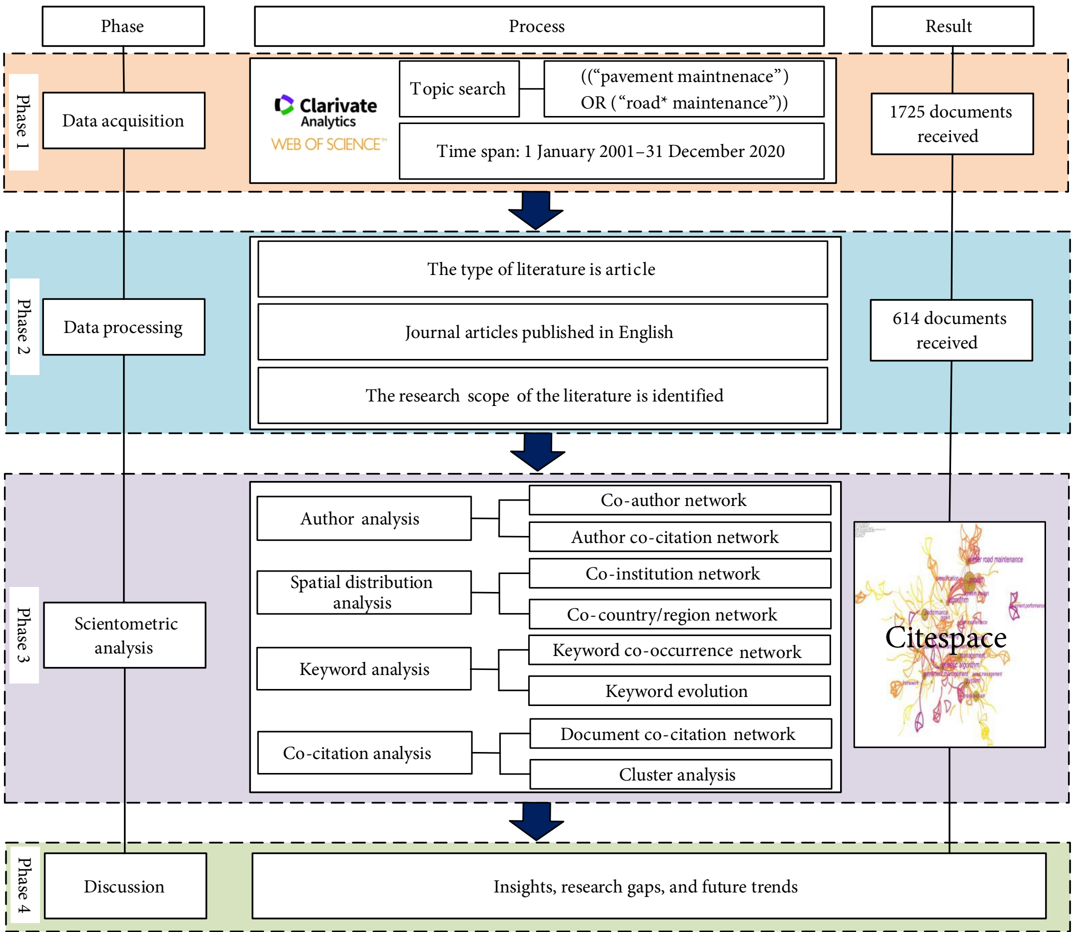

Figure 1. Overview of research design

1.2. Scientometric analysis

As a branch of informatics, scientometrics is used widely to analyze research impact, map knowledge structures, and identify development trends (Hess, 1997), which can give researchers and practitioners a global perspective of the current knowledge and research trends within a given research field (Abotaleb & El-adaway, 2018; Chen, 2017). Because of the wide range of research topics related to PM, existing research rarely focuses on analyzing the overall field through systematic literature analysis. Therefore, reported herein is a holistic scientometric review of PM supported by the software package CiteSpace (Chen, 2004, 2006) based on the interpretivist philosophical approach and inductive reasoning. The software package CiteSpace offers the unique advantage of analyzing and visualizing scientific literature by linking it systematically to help discover the knowledge hidden behind a considerable amount of literature. In addition, the review can be modified continuously as the research progresses, something that human researchers do not have sufficient capacity to do.

The present analysis involved several scientometric techniques that generated results from author analysis, spatial distribution analysis, keyword analysis, and document analysis. First, the author analysis was based on co-authorship analysis and co-citation analysis, where co-authorship analysis reveals cooperative networks for scientific knowledge at the micro-level (co-author), meso-level (co-institute), and macro-level (co-country), and the present ones at the meso- and macro-level are analyzed in Section 3.2, while co-citation analysis analyzes the process of generating new knowledge from different topics to current research and from dissociation to reorganization among authors; and authors with more citations are likely to be more influential than those with fewer citations. Second, keyword analysis was conducted based on keyword co-occurrence, which is used to detect the keywords in a set of documents, having the frequencies to indicate the relationships among them. In the present study, the identified keywords are likely hot topics in PM research; accordingly, how those keywords evolve is then identified. Third, document analysis was conducted based on co-citation analysis, then cluster analysis was conducted to classify the cited documents to identify emerging topics of interest. Finally, a research knowledge gap linking the existing research topics to future directions is proposed based on the captured knowledge status of PM.

2. Results

Figure 2 shows the distribution of the 614 research articles over the period of 2001 to 2020. As can be seen, PM has received continuous attention, with more articles published (and thus counted) every year. Since 2013, the number of articles published has increased gradually but steadily, the predicted number of articles can be seen from the trend line in Figure 2. It is expected that more research will be published in future years to enrich and expand the research topics and promote the development of PM.

2.1. Author analysis

The author analysis in a specific domain focused on collaboration and co-citation among authors, where the author collaboration analysis can reveal existing academic relationships among researchers (Ding, 2011; El-adaway et al., 2019), while the author co-citation analysis can identify the relationships among cited authors in the same publication and provides a way to understand the intelligent structure of PM research (Bayer et al., 1990).

2.1.1. Co-author network

As carriers of knowledge, authors play an important role in information communication and academic exchange. The information available from published articles can enable the identification of collaborations among authors to generate the co-author network for understanding the current author cooperation status and finding the influential authors, contributing to capturing specialists and expertise, thus increasing productivity and reducing the isolation to benefit scientific collaboration and promoting scholarly communications, which has been evidenced by the fact that publications generated through collaborations are published on higher impact outlets with more citations (Ding, 2011; Hosseini et al., 2018; Luwel, 2004). The generated co-author network is shown in Figure 3, where

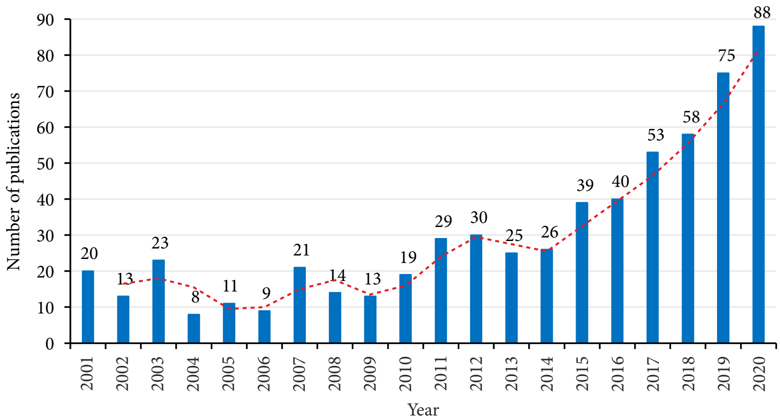

Figure 2. Distribution of source documents by 2001–2020 (614 publications in total)

there are 476 nodes and 370 links. Each node represents an author, with the node size representing their number of publications; each link between two authors denotes a collaboration, with the link thickness representing the strength of cooperation established through the co-author in the publications. Table 1 lists the eight authors with the most collaborations, with the top three being Zhanming Zhang (University of Texas), TienFang Fwa (National University of Singapore), and Adelino Ferreira (University of Coimbra). Those authors collaborate extensively with others, communicating and sharing knowledge, thus contributing to the promotion of the research field.

Figure 3 shows clearly the presence of several research communities in which many authors worked with one or more highly productive authors. In graph theory, the influence of an author is defined by the betweenness centrality in CiteSpace. A node with high betweenness centrality usually connects two or more large groups of nodes with the node itself in-between (Lu & Feng, 2009). The central author in a community is the one with the most collaborations. The largest community has Gerardo Flintsch as its central author and includes Tony Parry, Brian Diefenderfer, Tanveer Chowdhury, etc., and connects another community with Adelino Ferreira as the central author, including António Antunes, Luís Picado Sanitos, and Anabela Dos Santos Duarte; similarly, Zhanming Zhang has acted as the central author within his research community, consisting of Lu Gao, Kevin Gaspardb, Ivan Damnjanovic, and Seokho Chi. That is to say, those authors have collaborated with each other to promote publications, which have generated a broad impact and enriched the knowledge pool within the research field. However, in the whole network, the betweenness centrality of these nodes was zero, meaning that most of the authors do not collaborate substantially. Thus, the crucial cooperation between different research communities should be strengthened in the future, and more information communication and academic exchange are needed to ensure that research has relevance to practice and promote the development of PM. Overall, the findings derived from the map in Figure 3 and the list in Table 1 are described below.

I. Several collaborative communities and influential authors are identified to communicate and share knowledge creation to advance the research field. However, most authors are isolated without belonging to any community. Great efforts are needed to sustain the existing communities or to form more communities to enhance the transmission and creation of knowledge in the research field.

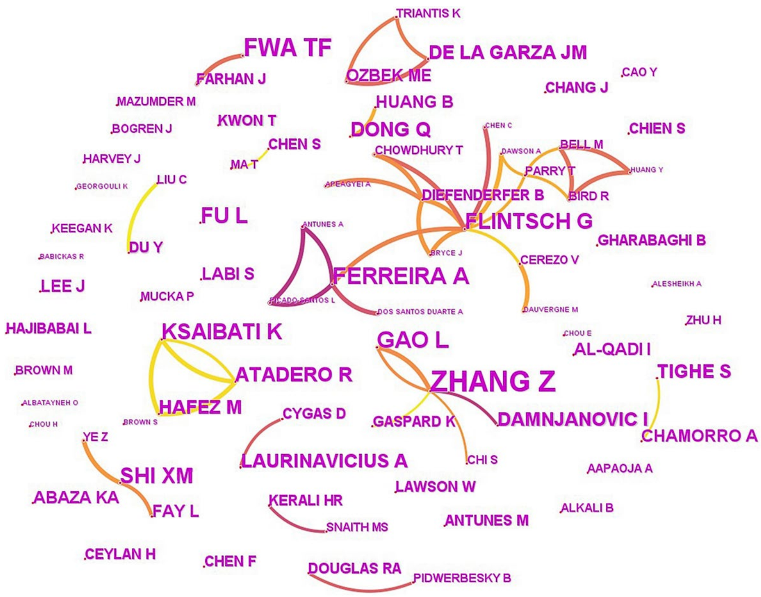

Figure 3. Co-author network

Table 1. Top 8 nodes of co-author network

Author	Institute	Country	Count
Zhang Z	The University of Texas at Austin	USA	15
Fwa TF	National University of Singapore	Singapore	10
Ferreira A	University of Coimbra	Portugal	8
Gao L	University of Houston	USA	8
Ksaibati K	University of Wyoming	USA	7
Fu L	University of Waterloo	Canada	7
Shi XM	Washington State University	USA	7
Flintsch G	Virginia Polytechnic Institute and State University	USA	7

2.1.2. Author co-citation network

Author co-citation analysis can identify the relationships among authors whose published articles are cited in the same articles. Organizations such as AASHTO (American Association of State Highway and Transportation Officials) and ASTM (American Society of Testing Materials) with high frequencies were removed from the list of influential authors because they issued many widely cited guidelines and affect the accurate analysis of the results. The generated author co-citation network is shown in Figure 4, where 66 out of the 668 nodes are presented, the node size represents the number of co-citations of each author, and the links between nodes reflect indirect cooperative relationships established based on co-citation frequency. The authors cited the most are identified, including TienFang Fwa (frequency = 50; Singapore), Ralph Haas (29; Canada), Khaled A. Abaza (13; Palestine), Zheng Wu (13; USA), Samer Madanat (13; USA), and Feng Wang (13, USA). Those cited authors have contributed the most to the development of PM, and the diversity of their locations indicates that PM research has been widespread around the world.

Based on the betweenness centrality scores, the top three authors are TienFang Fwa (centrality = 0.45), Ralph Haas (0.45), Kamal Golabi (0.34), and Samer Madanat (0.23). They are the major intellectual drivers of PM research and have connected research in different communities facilitating the development of PM. Additionally, several authors are identified by detecting rapid increases in citation frequency over short periods. The top identified bursts in the network are shown in Figure 5. Those authors tended to affect the direction of PM research in a specific period and their articles were worth following. Based on the above analysis, The findings that come to light based on the map in Figure 4 and Figure 5 are discussed below.

II. Most of the authors are connected and intertwined to form a community, indicating that the communication of knowledge exists among these authors, also demonstrating the homogeneity of their research, which tends to result in the exclusivity of research involving PM being focused on a few authors to the neglect of others, and furthermore causes research to concentrate on one subfield to the neglect of other subfields, which is not conducive to the diversity of research, requiring sufficient attention and concern.

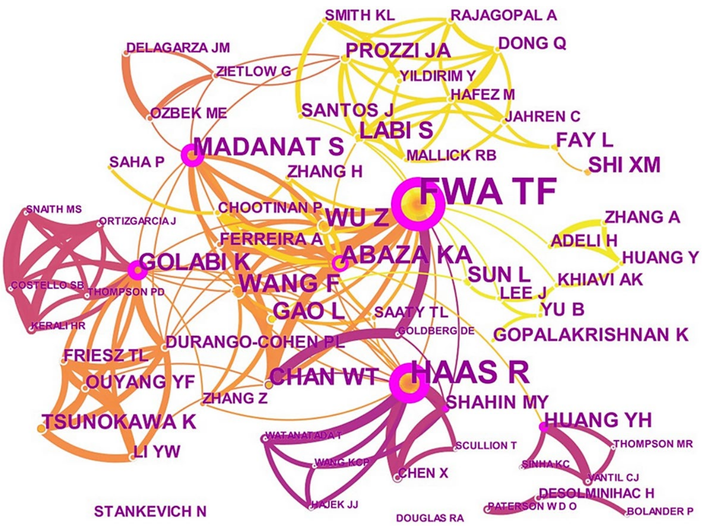

Figure 4. Author co-citation network

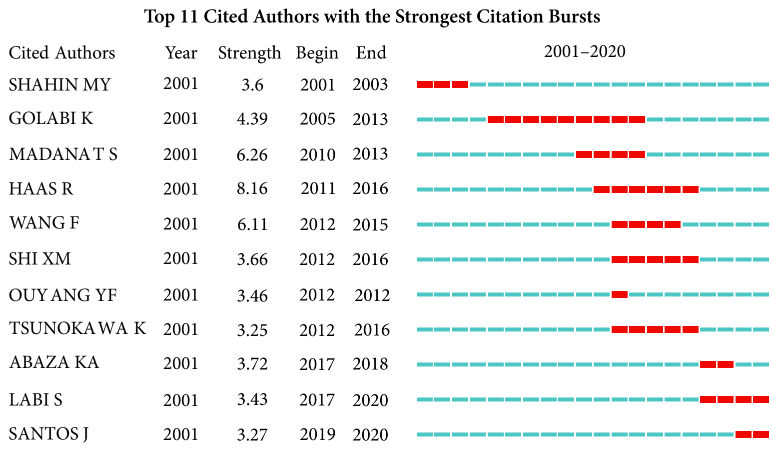

Figure 5. Top authors with co-citation bursts

2.2. Spatial distribution analysis

This research provided the network to explore the spatial distribution of research publications on PM, including the co-institution analysis and co-country analysis, which can reveal existing academic relationships among institutions and countries, respectively, and identify the top institutions and influential countries in the field of PM.

2.2.1. Co-institution network

In addition to the collaboration activities of individuals, identifying the collaboration network of institutions is significant for revealing the research strength of institutions, and facilitating visits to learn, particularly in terms of contributing to research partnership policy-making (Ding, 2011; Hosseini et al., 2018). Figure 6 shows the collaboration network between institutions with 387 nodes and 294 links. The node size represents the number of published articles per institution; the link thickness between institutions denotes the level of cooperation established through the co-institution in the published articles. In Figure 6, the University of Texas at Austin (19 published articles), University of Waterloo (16), Southeast University (16), Vilnius Gediminas Technical University (13), and National University of Singapore (12) top the list, showing that those institutions have made significant contributions to PM research and can be publication centers for PM research around the world. Those institutions surely excel in terms of research input and policy making and implementation for research partnerships that advance research in the field, being worthwhile for researchers and institutions to learn from.

Additionally, the nodes with high betweenness centrality were identified. Institutions such as Georgia Institute of Technology (centrality = 0.01), University of Waterloo (0.01), Southeast University (0.01), University of Illinois (0.01), Chang'an University, and The Hong Kong Polytechnic University (0.01) are the key nodes in the network and play a significant role in international communication and cooperation for promoting academic exchange and sharing intellectual knowledge related to PM. Furthermore, citation bursts were identified to find notable increases in citations over a short period. The University of Texas at Austin (burst strength = 3.87; 2008–2014), Montana State University (3.05, 2011–2013), Vilnius Gediminas Technical University (3.54; 2015–2017), Southwest Jiaotong University (3.41; 2016–2018), Tongji University (3.29; 2017–2020), Chang'an University (3.34; 2018–2020), and University of Wyoming (3.18; 2018–2020) are at the forefront, indicating that their research attracted extraordinary attention in the corresponding years. Note that two citation bursts have emerged in the past three years for Chang'an University and the University of Wyoming, signaling that Chang'an University and the University of Wyoming are receiving worldwide attention and are likely to be central to developing the field further in the future. Those rapidly growing institutions are in the spotlight primarily because of their strong research strengths in the research field, demonstrating that they are advancements in need of attention. Overall, the findings derived from the analysis are described below.

III. Although several institutions collaborate with each other, the fact that numerous institutions are scattered, illustrating the isolated nature of research in institutions. A few influential institutions play a promising role in the research process, but extensive interweaving networks of collaboration are not formed, revealing that knowledge communication and sharing among researchers in those institutions with other researchers is still lacking. In addition, leading and strong scientific research institutions are explicitly identified that could help to cultivate PM researchers, while noting the necessity for improving communication and collaboration among researchers between institutions.

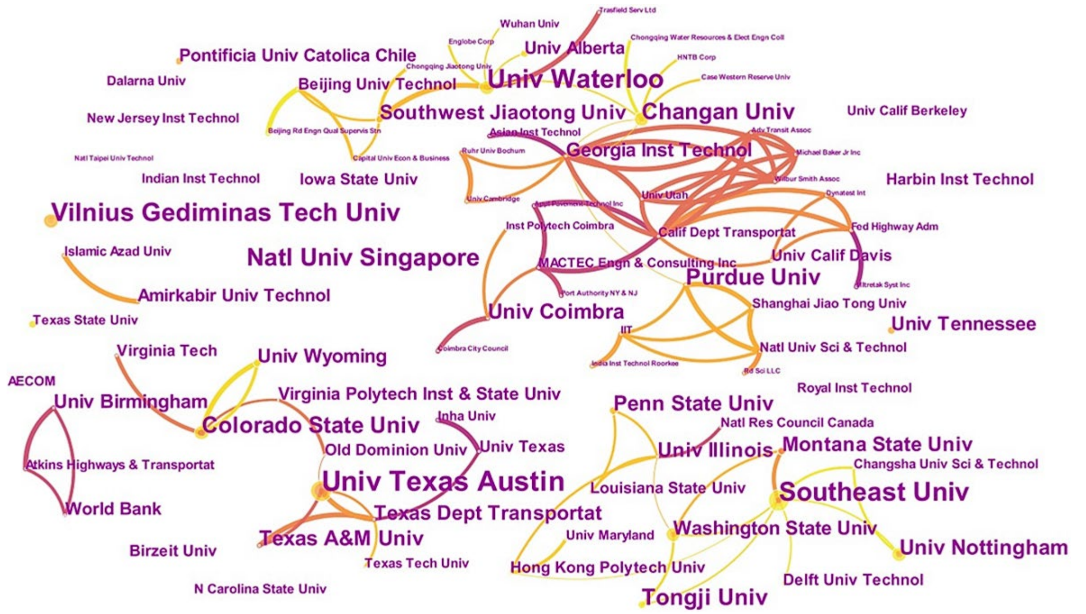

Figure 6. Co-institution network

2.2.2. Co-country network

Similarly, a network was created based on the contributions of countries to identify the influential ones and map the collaborations among them. As shown in Figure 7, the network contains 67 nodes and 92 links; the node size represents the total number of articles published in a country. In Figure 7, the USA (263 published articles), China (94), Canada (51), England (29), Portugal (19), South Korea (18), and Australia (18) are the top countries that have made significant contributions to PM research. That those countries published more articles implies that their PM research is more advanced. Regarding publications by countries, the USA has contributed the most to developing PM, and China is the second-largest contributor, but still a gap between it and the USA. In addition, regarding international collaborations, researchers from the USA have collaborated widely with those from other countries, such as South Korea, Israel, and China.

The betweenness centrality is identified, with USA (centrality = 0.57), England (0.15), China (0.13), France (0.12), Poland (0.12), and Australia (0.11) being the most influential countries. The fact that the USA has the highest centrality shows that it occupies the most important position in the network and connects research activities among different countries for sharing knowledge on PM. Interestingly, USA links with other countries are not strong, rather New Zealand shows strong links with England and North Ireland respectively. Thus, the governing bodies of the pioneering country need to redefine the policies to promote cooperation, and serve as an example for other countries, working together to promote the overall level of knowledge in PM. The findings can be described as follows.

IV. Few countries are present in the network while most in the world lack research concerning PM. Also, the links among the countries present in the network are limited but still need to be enhanced either by adapting policies or by increasing investment. Moreover, developing countries are underrepresented in the network. Those countries are isolated from the mainstream in terms of both resource input and technology available, which is highly detrimental to the development trend. This is also a serious obstacle to global development trends, which may require negotiated global organizations to be mitigated.

2.3. Keyword analysis

Keywords are relevant for describing the core content of published articles and demonstrating the range of areas researched within a given domain (Martinez et al., 2019). This subsection contains two parts, namely (i) keyword co-occurrence and (ii) keyword evolution. The keyword co-occurrence network identifies research topics in a specific domain, while the evolution network reveals the development of the research field over time.

2.3.1. Keyword co-occurrence network

A network is generated by setting pathfinder pruning in CiteSpace. When creating the network, some general keywords (e.g. "maintenance", "pavement maintenance", "road maintenance", "road") are removed because they fail to reveal related research trends and make the analysis less accurate. The generated network comprises 414 nodes and 678 lines as shown in Figure 8, where node size represents the frequency of words in the documents, and the links indicate the interrelatedness between a pair of keywords. Furthermore, Table 2 lists the top 48 keywords with a total of 503 co-occurrence frequencies. Notably, to avoid manual bias, this research retains the original output provided by CiteSpace.

Figure 8 and Table 2 show the main areas identified in PM research. The most prominent item in PM research is 'model', appearing 61 times. This means that they have been researched widely, from which it is reasonable to conclude that it is the basic component in PM research.

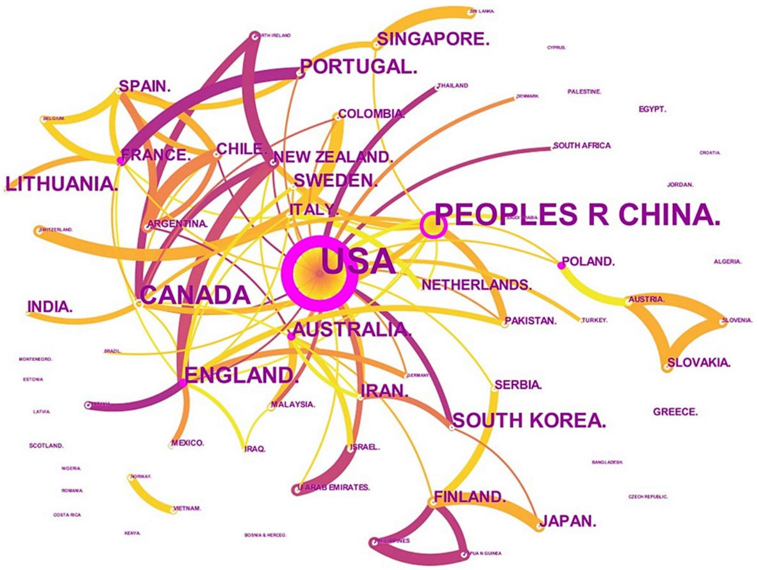

Figure 7. Co-country network

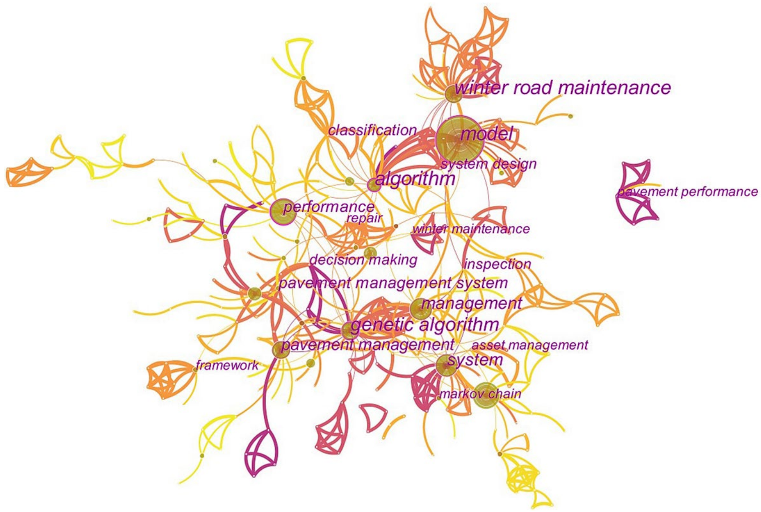

Figure 8. Keyword co-occurrence network

Table 2. Top keywords with their frequencies in pavement maintenance (PM) research

Frequency	keyword	Frequency	keyword	Frequency	keyword
61	Model	7	Roads & highway	4	Classification
30	Performance	7	Rehabilitation	4	Time
30	Genetic algorithm	7	Concrete	4	Crack detection
29	Management	6	Methodology	4	Skid resistance
28	System	6	Pavement performance	4	Pavement deterioration
28	Optimization	6	Winter maintenance	4	Asphalt mixture
25	Winter road maintenance	6	Markov chain	4	Artificial neural network
22	Pavement management	5	Asset management	4	Repair
21	Algorithm	5	Highway maintenance	4	Chip seal
19	Asphalt pavement	5	Flexible pavement	4	Analytic hierarchy process
14	Pavement management system	5	Crack sealing	4	Binder
12	Construction	5	Network	4	Asphalt
9	Multiobjective optimization	5	Selection	4	Inspection
8	Framework	4	Design	4	Mixture
8	Life cycle assessment	4	Data collection	4	Decision making
8	Prediction	4	Safety	4	Cost

In practice, however, the models constructed are generally nonlinear multi-objective polynomial problems that risk becoming prohibitively computationally demanding and complex; this issue must be addressed, with continuous improvement in algorithms being the key to breaking through this bottleneck. In the list of top keywords in PM research, "algorithm" is highly used (21 times). For instance, Chang (2013), Suresh and Kumarappan (2013), and Ahmed et al. (2019) used the particle swarm optimization algorithm successfully to find optimal PM strategies. Accordingly, genetic algorithms (GAs) ("genetic algorithm"; keyword frequency = 30) are used for model solutions or optimization. For example, Morcous and Lounis (2005) and Chootinan et al. (2006) used GAs to search for optimal maintenance alternatives by minimizing the life-cycle cost, and Bosurgi and Trifirò (2005) researched PM management based on artificial neural networks and GAs.

Additionally, model development and application are done to improve pavement performance. In the list of top keywords in PM research, "performance" ranks highly, appearing 30 times. In highlighting this association, we refer to the work of Vyas et al. (2021), who proposed using a SWOT (strengths, weaknesses, opportunities, and threats) model and the fuzzy analytic hierarchy process to prioritize pavement sections and formulate a strategy to assess pavement condition for PM. Accordingly, "optimization" (6 times) and "multiobjective optimization" (5 times) are considered frequently for PM strategies, and as well as taking pavement performance as one of the objectives, the general optimization factors include cost (Yu et al., 2015, 2019), toll pricing (Saha et al., 2014), budget (Amin et al., 2019; Yepes et al., 2016), the delay caused by the PM scheme (Ma et al., 2018), and environment (Giustozzi et al., 2012). Through modeling and optimization, strategies can be implemented more efficiently to improve pavement performance.

The performance issue also pertains to design. In the list of top keywords in PM research, "design" is an important research topic, with a frequency of 4. Designers can identify risks and optimize the strategies during the PM design stage. Essentially, how materials perform is an important consideration. Substantially, in the process of PM, material performance selection may be the first step, and that performance directly affects pavement performance. As Table 2 shows, concrete (frequency = 7), asphalt pavement (5), flexible pavement (5), asphalt mixture (4), asphalt (4), and mixture (4) are the important materials in PM. Furthermore, regarding their application in PM, attention should be given to new materials such as basalt-fibre-reinforced concrete (Sun et al., 2019). In addition, the life cycle assessment is generally applied, appearing 4 times, and this topic is usually related to prediction (4), involving pavement performance prediction using Markov chain (4) and parameters of pavement deterioration (4), and also to cost (4) and decision making (4).

In the list of top keywords in PM research, "management" is the fourth-highest research item, occurring 29 times, and "pavement management" is also ranked highly, occurring 22 times. Good pavement management is essential for adequate PM because it has the potential to provide decision-makers with the tools needed for effective and sustainable pavement management (Santos et al., 2017). This relates to the inspection and maintenance management of the pavement, where the keywords of the inspection management included in Table 2 are data collection (4), classification (4), crack detection (4), artificial neural network (4), and inspection (4). While the keywords involved in maintenance management are winter road maintenance (6), rehabilitation (4), winter maintenance (4), highway maintenance (4), crack sealing (4), repair (4), and chip seal (4). Those can be achieved efficiently with a system, and "system" and "pavement management system" are also an important topic in PM research, occurring 28 times and 5 times, respectively. A management system can facilitate efficient data exchange and information management in the process of pavement management, generating a large quantity of information and documents. More importantly, a management system can assist managers in planning, analyzing, and maintaining roads at the right time with the right materials and budget availability (Peraka & Biligiri, 2020).

In addition, some keywords received relatively high betweenness centrality scores, such "algorithm" (centrality = 0.36), "genetic algorithm" (0.30), "model" (0.24), "performance" (0.24), "inspection" (0.18), "winter road maintenance" (0.16), "system" (0.14), "pavement management" (0.14), "decision making" (0.14). Keywords with high betweenness centrality connect different research topics and significantly influence the development of PM research, further revealing the hot topics in PM research. Considering these results, "algorithm", "genetic algorithm", and "performance" – as the three most prominent research topics – are attracting increasing research attention for promoting PM management. With respect to these findings, the following observations remain of interest.

V. PM research covers many subfields, but those attentions are not uniformly distributed, where more effort is devoted to subfields such as model, performance, genetic algorithm, and management, and less to asphalt mixing, decision making, etc. That is to say, more research focuses on PM strategy making, while less attention is paid to the hard aspects such as PM material properties.

VI. LCA has gained considerable attention to become a cause for concern. LCA offers a systematic consideration within the life cycle, enabling sound decisions to be made by viewing PM from a holistic viewpoint, which tends to include environmental impacts, so as to reduce resource waste and realize sustainable development, thus being a promising direction for advancement.

VII. Less attention has been paid to the information technology applications for inspection, such as artificial intelligence technology. Traditional inspection relies heavily on manual, vehicle, and other mechanical equipment, which is time-consuming, laborious, and inefficient. The rising information technologies in recent years offer great potential for inspection, which can be treated as a serious gap within the existing literature in PM. Applying information technologies to PM is a practical and valuable direction that warrants devotion.

2.3.2. Keyword evolution

A keyword co-occurrence network is a static representation of a research field without considering its dynamics over time (Zhong et al., 2019). For insight into the dynamics of keywords over time, the documents are divided into four distinct five-year periods to reveal changes in PM trends. Using keyword co-occurrence networks and word clouds, Figure 9 shows how the keywords have evolved over time. As can be seen, as PM research has matured, the research contents and methods have undergone subtle but obvious changes.

The high-frequency keywords include "model" and "optimization", indicating that they are the basic components of PM research and have attracted research attention. Early PM research tended to rely on manual data collection for further analysis to establish PM models. For example, many studies used Markov-chain models to predict pavement performance for PM based on historical data (Gao & Zhang, 2013; Kobayashi et al., 2010; Lethanh & Adey, 2013; Thomas & Sobanjo, 2013). Other models were also established for PM. For example, Van Noortwijk and Frangopol (2004) and Tuttle (2005) established models respectively to analyze pavement deterioration for maintenance based on the previously collected data, and those models can be used to develop strategies to ensure pavement performance. In early optimization research, the factors considered for optimizing PM were often directly observable ones. For instance, Ng et al. (2009) considered vehicle dynamics to minimize user delays as well

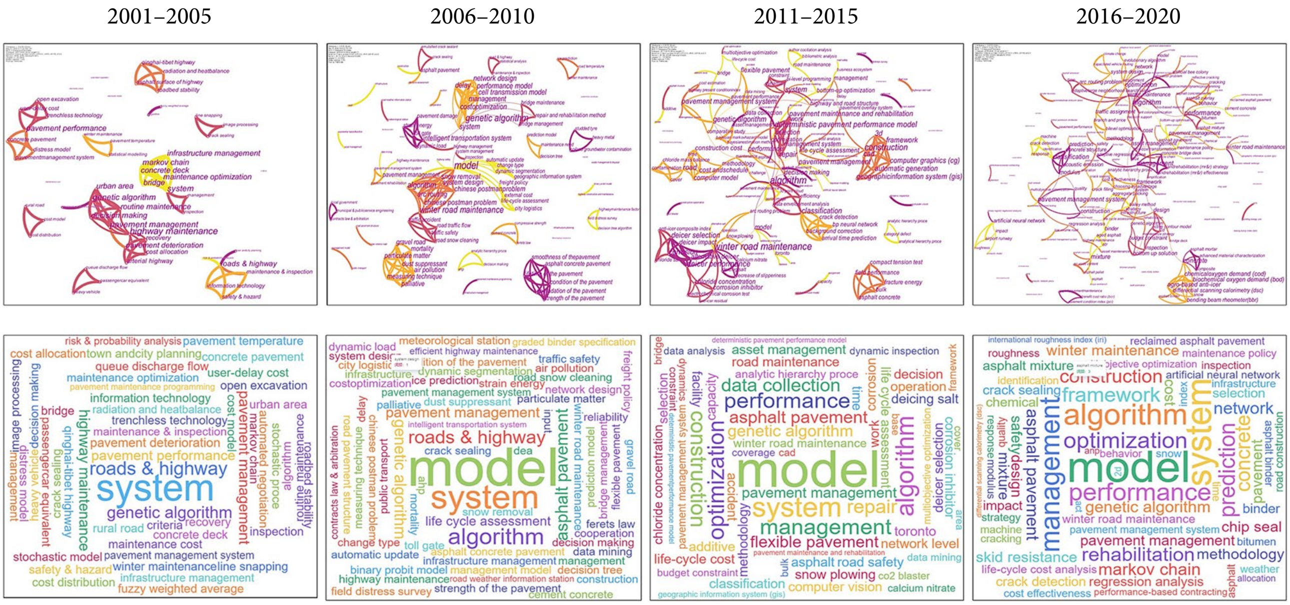

Figure 9. Keyword evolution

as maintenance costs to optimize PM planning. Elhadidy et al. (2015) optimized the multi-objectives for PM and rehabilitation strategies by considering the action costs and conditions for the used road network. Indeed, those methods show good performance for specific scenarios. However, the data obtained from models or simulations as a reference for decision-making cannot replace real data completely, and inaccuracy in the results may damage maintenance operations, with undesirable consequences such as economic losses and waste of resources. Meanwhile, the consideration of optimization factors requires a more comprehensive and in-depth analysis.

Current PM research has researchers employing novel techniques that can give robustly representative features, such as 3D techniques, convolutional neural networks, and machine learning. For instance, Zhang et al. (2018b) and Vázquez-Méndez et al. (2018) proposed a 3D model for characterizing pavements, it is useful to parameterize pavements to obtain information about them. Hoang et al. (2018), Maeda et al. (2018), and Hoang (2019) developed novel methods based on convolutional neural networks/machine learning algorithms to detect pavement distress for surveying pavement conditions. Likewise, Yao et al. (2020) used machine learning to develop better maintenance strategies that maximize long-term cost-effectiveness in maintenance decision-making, obtaining good results. In current optimization research, environmental factors are considered in the maintenance process to promote sustainability. For example, as an objective, Lee and Madanat (2017), France-Mensah and O'Brien (2019) and Wang et al. (2020) incorporated greenhouse gas (GHG) emissions in the decision-making process. Additionally, users' satisfaction or willingness to travel (Zhang et al. 2018c) should be considered for the PM. Although these researchers have attempted to employ such techniques in PM, putting such techniques into practical application involving huge pavement networks and numerous countries still has a long way to go. In addition, the other findings can be described as followed.

VIII. In the last two decades, the main concern sub-areas of PM research have hardly changed, primarily focusing on model, system, performance, management, algorithm, etc. That is to say, most of the PM research in the last two decades has focused on PM strategy development, which indeed enhances pavement maintenance from the management aspect, but the pavement inspection and pavement material properties are less studied, which is a problem deserving serious thoughts that require more investment.

2.4. Document analysis

Done to establish the influential published articles and research themes, the document analysis comprised (i) the document co-citation network and (ii) cluster analysis. A document co-citation network is a network of co-cited references that represents the relationships among citations at an individual level; it shows the quantity and authority of references cited by publications. Cluster analysis aims to discover the semantic themes hidden in textual data and explore the structure of a scientific knowledge domain (Chen et al., 2010).

2.4.1. Document co-citation network

Table 3 lists the five most influential documents in terms of normalized citations, those being the articles by Morcous and Lounis (2005), Koch et al. (2013), Huang et al. (2009), Abaza et al. (2004), and Chootinan et al. (2006), which were cited 116, 92, 85, 83, and 77 times, respectively. Those articles were widely recognized by peers, had high value for researching PM, and can be seen as the major knowledge-sharing points in the research field. Morcous and Lounis (2005) presented a method for deter-

Table 3. Four most-cited publications

No.	Author	Title	Total citation	Source
1	Morcous and Lounis	Maintenance optimization of infrastructure networks using genetic algorithms	116	Automation in Construction
2	Koch et al.	Automated pothole distress assessment using asphalt pavement video data	92	Journal of Computing in Civil Engineering
3	Huang et al.	A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation	85	Transportation Research Part D –Transport and Environment
4	Abaza et al.	Integrated pavement management system with a Markovian prediction model	83	Journal of Transportation Engineering
5	Chootinan et al.	A multi-year pavement maintenance program using a stochastic simulation-based genetic algorithm approach	77	Transportation Research Part A – Policy and Practice

mining the optimal set of maintenance alternatives for infrastructure networks based on a GA and a Markov-chain model for the optimal maintenance strategy. Koch et al. (2013) presented a method for detecting potholes when assessing pavement conditions, achieving high precision and recall based on the collected pavement video. Huang et al. (2009) applied an LCA model for PM considering traffic, and this can quantify the environmental impact of PM work. Abaza et al. (2004) developed an integrated pavement-management system for planning and scheduling PM and rehabilitation work, and this system can assist managers in efficient decision-making. Likewise, Chootinan et al. (2006) proposed a method integrating stochastic simulation and GA for multi-year pavement maintenance planning, showing in the results that the method performed well. Those documents served as significant cornerstones in PM research that inspired or provided the base for many subsequent studies, and they have contributed fruitfully to the development of PM research.

Figure 10 shows the document co-citation network with 660 nodes and 1558 links. The document co-citation analysis was performed on 614 retrieved documents; the node documents are among the cited documents and are not necessarily included in the 614 retrieved documents. As shown in Figure 10, the four most cited articles were those by Wu and Flintsch (2009) [10 co-citations], Fay and Shi (2012) [eight], and Ouyang and Madanat (2004, 2006) [eight and seven, respectively]. Wu and Flintsch (2009) and Ouyang and Madanat (2004, 2006) conducted research on optimizing road maintenance activities, and their research had a profound impact on subsequent research. Fay and Shi (2012) introduced the environmental impact of chemicals used for snow and ice control on the pavement in winter, and their study is an essential resource for winter PM. Those documents occupy significant influence in their respective research communities, contributing to the growth of their respective research communities.

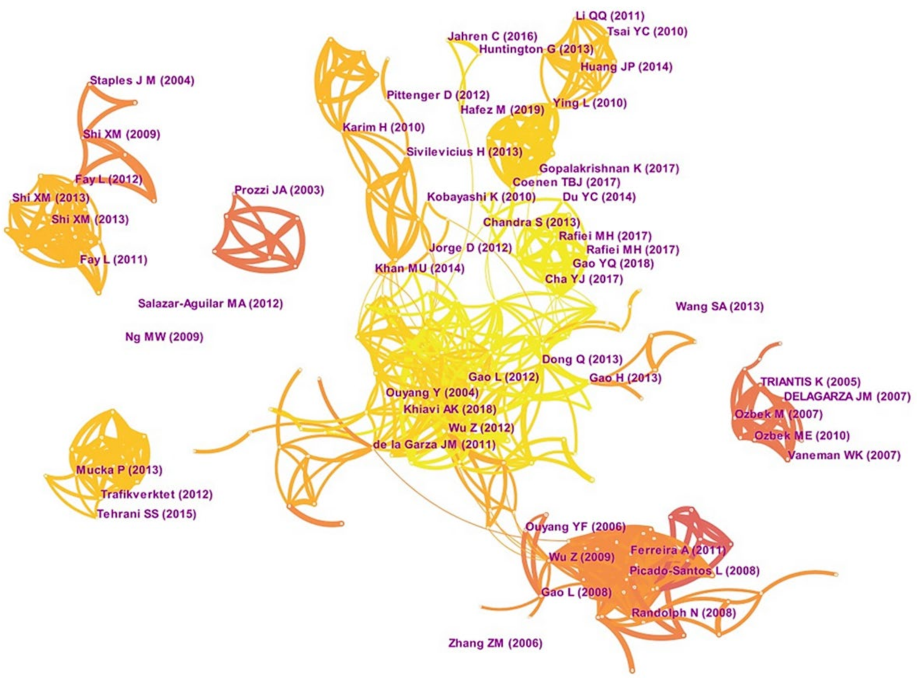

Figure 10. Document co-citation network

As seen presently, the betweenness centrality is also identified, and some articles are notable. For instance, those by Wu et al. (2012) each have a betweenness of 0.04, Gosse et al. (2013), de la Garza et al. (2011), Dong et al. (2013), Cha et al. (2017), and Coenen and Golroo (2017) each have a betweenness of 0.02. Those articles are the foundation of PM research and have an important influence on the development of PM. Based on the above analysis and in view of the research documents in this field, several facts pertaining to the PM documents are able to be informed. This will be discussed below.

IX. The documents form communities that are isolated and disconnected from each other. Among those communities, only a few have sparse or even no connections, and most of the citations are generated within the communities, indicating that the communities are almost closed and that researchers neglect to borrow applicable theories and findings from studies outside the communities, thus failing to benefit from theories and ideas from other communities.

2.4.2. Cluster analysis

Cluster analysis is an essential step in identifying patterns and trends in a body of knowledge based on a document co-citation network (Chen & Morris, 2003). Here, clusters generated from tightly connected co-cited references were detected and labeled using the terms extracted from the keywords, title, or abstract by CiteSpace (Cobo et al., 2011).

Figure 11 shows the clusters labeled with keyword terms. The label for each identified cluster was generated using the log-likelihood ratio (LLR) algorithm because the LLR is useful for selecting the best cluster labels in terms of uniqueness and coverage by comparing the likelihood of finding a term in one cluster against that of finding exactly the same term in another cluster (Chen et al., 2010; Olawumi & Chan, 2018). Table 4 presents detailed information about the clusters (e.g., size, silhouette, label). A silhouette value above 0.7 indicates a highly reliable cluster, and a silhouette value close to 1 indicates a strongly homogeneous cluster (Chen et al., 2010; Hosseini et al., 2018). In Table 4, the silhouette scores range from 0.885 (cluster 0) to 1 (clusters 1, 2, 6–8), showing that the clusters are sufficiently consistent. The size of a cluster indicates the number of published articles therein; with 78 published articles, cluster 0 is the largest. Additionally, clusters are labeled by mean year because they contain both recent and older documents. Accordingly, ranging from −1 to 1, the modularity indicates the quality of the overall network division; a network with modularity close to 1 comprises isolated clusters (Chen, 2004; Newman, 2006). Figure 11 shows high modularity of 0.9203, indicating that the generated network is well-structured with clear boundaries. With regard to these findings (Figure 11; Table 4), the following observations are worth noting as followed.

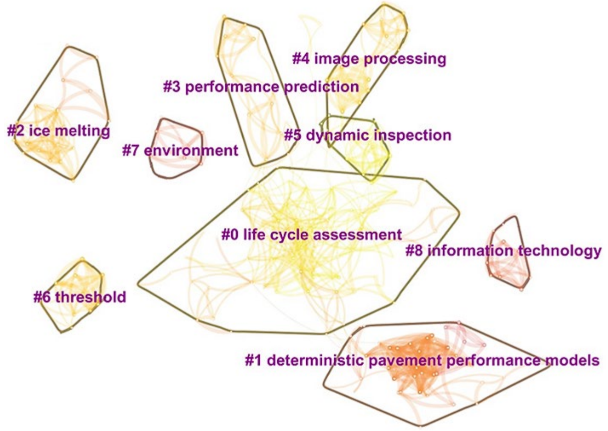

Figure 11. The clustering results in LLR algorithm

X. Those clusters have clear boundaries and few intersections among them, demonstrating that the clusters are isolated from each other with a lack of mutual influence and learning. Notably, Clusters 4 and 5 are intersecting, showing that studies between the two clusters have an exchange of theory and ideas, which can easily contribute to the promotion of research within the clusters. In addition, the research themes reveal a preponderance of research involving management strategies and relatively little applied to the operation, as previously analyzed, which limits the development of such an interdisciplinary field and its corresponding industries.

Cluster analysis allows to identify the potential research themes in document data and can transform unstructured data into structured data objects, revealing the underlying knowledge structure of the research domain for discovering knowledge (Chen et al., 2010; Hosseini et al., 2018). Additionally, from the cluster and keyword results, there exist relationships between clusters and keywords in that they have terms with similar or identical meanings. The hidden connection is that the cluster is formed by tightly connected co-cited documents, while the core content of the document research is generally described by keywords, resulting in the keywords from tightly connected co-cited documents being in a relationship with the cluster. That is to say, a limited number and similar meaning of keywords in the tightly connected co-cited documents can form a cluster as a body of knowledge, where the keywords are viewed as the knowledge base and the cluster is viewed as the knowledge structure to form the knowledge domain. The detailed cluster analyses are as follows.

As seen in Figure 11 and Table 4, the most significant cluster is that for LCA (cluster 0), which is an important method for systematically evaluating and identifying the influencing factors throughout the life cycle (Luo et al., 2019), including the PM stage. In addition to pavement performance and maintenance costs, environmental impact assessment (Lidicker et al., 2013; Santero et al., 2011a; Yu & Lu, 2012) is an important consideration. It is reasonable to think of the pavement network itself as having a significant environmental impact, which is handled through components native to the materials and construction.

Also, traffic delay (de Souza & de Almeida Filho, 2020; Ma et al., 2018; Santero et al., 2011b) and vehicle–pavement interaction (Ng et al., 2009; H. Wang & Z. Wang, 2013) show promising opportunities for reducing environmental impact, particularly as the supporting models and science continue to improve (Santero et al., 2011a). For PM, LCA emphasizes the need to improve pavement performance, reduce maintenance costs and minimize environmental impact by optimization, which could help decision-making to guide maintenance activities with coordinated working. For instance, Lee et al. (2016) provided a case that conducts maintenance on specific pavement segments to meet the minimization of lifecycle costs and the GHG emissions constraint; that work is an important reference for applying LCA in PM development. Applying LCA to PM modeling is a significant issue: it is conducive to (i) determining the cost and benefit of PM and (ii) evaluating pavement performance and environmental impact. Likewise, cluster 7 contains some LCA studies.

The second most significant cluster is that for deterministic pavement performance models (cluster 1), which aims to improve pavement performance by models for determining maintenance and rehabilitation, including studies related to maintenance design and materials. Maintenance design is a fundamental step in conducting maintenance activities; in particular, it determines the pavement structure, which affects the rolling resistance (Chupin et al., 2013). Reasonable PM design improves pavement performance, minimizes maintenance costs, and extends pavement service life (O'Flaherty & Hughes, 2015). For instance, Abaza (2005) entered the parameters of the pavement performance curve into a flexible pavement overlay design model to compensate for the loss in performance, thereby improving the pavement performance over a specified service time. PM and rehabilitation also refer to materials. To begin with, considering the material in the design phase is important, which is related to the quality of PM and rehabilitation. The thickness and material properties of each layer forming the pavement structure will affect the deformation of the pavement under a given load (Abaza, 2005; Santero, 2009). The main commonly used pavement materials are asphalt and concrete, and most studies provide some comparisons between concrete- and asphalt-based pavement options. In addition, many studies (Bressi et al., 2016; Fu et al., 2017; Saberian et al., 2019) explored new pavement materials and their performance by adding new composite reinforcing materials. Those explorations offer the potential for improving pavement performance and help to promote the development of PM. Additionally, cluster 2 describes ice melting; this cluster contains studies of how snow and ice affect pavement materials in winter, and those studies have very similar research themes focused on practical issues.

Another main cluster (cluster 3) is related to performance prediction. Because of pavement deterioration in uncertain complex conditions, there is an urgent need to be able to predict pavement conditions for PM because doing so offers the potential to characterize pavement performance, thereby guiding the PM activities. Therefore, modeling pavement performance is important. Chou and Le (2011), Jorge and Ferreira (2012), and Lethanh and Adey (2013) applied different methods for pavement performance prediction respectively and all of them achieved positive results. Additionally, the prediction of pavement performance usually considers some non-ignorable factors such as flooding (Khan et al., 2014), and loadings (Chou & Le, 2011; Sivilevičius & Vansauskas, 2013), this being because full consideration offers a convincing reference for making maintenance decisions. Accordingly, cluster 6 targets describing the pavement structure by setting thresholds to assess pavement performance for pavement maintenance. There are several measurement indicators of pavement performance, such as road unevenness indicators (RUIs) (Múčka, 2013) and the International Roughness Index (IRI) (Tehrani et al., 2015; Johannesson et al., 2016). Those clusters describe and reflect the pavement performance, thereby driving researchers and practitioners to adopt PM for better pavement performance.

Table 4. Documents co-citation clusters

Cluster ID	Size	Silhouette	Mean year	Cluster label (LLR)	Research theme	Representative document
#0	78	0.885	2013	Life cycle assessment	LCA	de la Garza et al. (2011), Mathew and Isaac (2014)
#1	40	1	2007	Deterministic pavement performance models	Practice	Ouyang and Madanat (2006), Wu and Flintsch (2009)
#2	21	1	2010	Ice melting	Practice	Fay and Shi (2012), Shi et al. (2013)
#3	17	0.987	2011	Performance prediction	Theory	Abaza (2016), Sivilevičius and Vansauskas (2013)
#4	16	0.977	2013	Image processing	Technology	Ouma and Hahn (2016), Zalama et al. (2014)
#5	14	0.996	2016	Dynamic inspection	Technology	Cha et al. (2017), Maeda et al. (2018)
#6	14	1	2013	Threshold	Theory	Múčka (2013), Tehrani et al. (2015)
#7	12	1	2005	Environment	LCA	Prozzi and Madanat (2003)
#8	11	1	2005	Information technology	Technology	Ozbek et al. (2010), Vaneman and Triantis (2007)

Labeled "image processing" in Figure 11 and Table 4, cluster 4 is related to machine learning. Improving the automation of obtaining pavement performance and detecting and identifying distress is commonly considered to be a fundamental task for adopting efficient and cost-effective PM measures. Therefore, machine-learning-based technology is worth promoting and should be developed across a broad spectrum. For example, Yousaf et al. (2018), Hoang (2019) and Marcelino et al. (2021) used machine-learning approaches including support vector machines to conduct detection on pavement distress. Furthermore, deep-learning methods have been applied in PM research. Gopalakrishnan et al. (2017) and Ni et al. (2019) proposed different deep-learning-based methods to automatically detect images for target object identification. In addition, distress quantification can provide in-depth information about pavement conditions, which can be integrated into detection techniques to produce convincing results. Yang et al. (2018), Kim and Cho (2019), and Ji et al. (2020) carried out useful studies that are important references for quantifying detected distress. Moreover, other techniques – such as 3D ones (Huang et al., 2014; Zhang et al., 2017, 2019) and unmanned aerial vehicles (Inzerillo et al., 2018; Li et al., 2019; Outay et al., 2020; Wu et al., 2019) – were adopted to support PM by collecting and extracting information. Note that most of the articles in cluster 4 were published between 2010 and 2019, indicating that this cluster is the emerging core of PM knowledge. Additionally, cluster 5 and 8 also describes research on PM technologies. These clusters focus mainly on advanced technology-related studies in PM research.

3. Discussions

3.1. Insights of the PM research

In the present research, a large amount of existing literature on PM research was reviewed by scientometric analysis, through which the chosen approach allows visualizing the existing knowledge and finding hidden connections for in-depth analysis of knowledge structures and research topics by complementing integral studies with a strong quantitative approach delivered through science network mapping tools. In light of the analysis results, the theoretical and practical implications of this research can be summarized as follows.

3.1.1. Theoretical implications

First, this research maps several knowledge networks in the field of PM using Citespace and reveals the structural patterns of knowledge communication and sharing networks, including author, institution, country, keyword, and document network analysis. The mapping results exhibit global and homogeneous interactions among researchers around the world, and the knowledge exchange networks illustrate closed and decentralized structural patterns that highlight the critical role of individuals or groups in knowledge communication and sharing activities. The findings of those results contribute to revealing the current knowledge structure and status, benefitting an in-depth understanding of the interaction mechanisms of the PM field.

Second, although communication and cooperation have facilitated the diffusion of knowledge and the creation of novel knowledge, the current PM field is still limited from the perspective of world development. This research reveals that current research tends to be mostly homogeneous and dispersed with few emerging extended subfields, indicating a strong dependency on knowledge self-formation sharing and promotion within the field. Those findings enrich the understanding of the dynamic development process of the PM field.

Third, this research provides an in-depth and comprehensive understanding of research trends in the field of PM and systematically and comprehensively captures hot topics, also, the formation and deduction of knowledge are analyzed jointly from both static and dynamic perspectives by adopting an interpretive philosophical approach and inductive reasoning. Those findings hold the promise of considering future developments and proposing to complement the past through a critical perspective and holistic views, contributing to the improvement and development of the PM field.

3.1.2. Practical implications

First, this research reveals the closed and decentralized network structure pattern of PM field research, where a few individuals and teams occupy a key role in the communication and sharing activities, so that establishing connections with these individuals or teams can be given priority in conducting PM research through visiting exchanges or project collaboration. In the process of knowledge diffusion and innovation, these individuals or teams can be regarded as nodes to achieve leapfrog coordination and interaction. In addition, communication and cooperation should be strengthened to avoid the formation of network silos.

Second, the homogeneity and dispersion of knowledge and the limitations of research subfields have constrained the development of the PM field, bringing to light the need to enhance communication and collaboration for benefiting from the theories and ideas of other communities and thus enriching the PM research field and knowledge pool. A workable approach is to expand the boundaries of the PM field and reduce the cost of communication and collaboration to facilitate the collision of theories and ideas from different fields, fostering positive and innovative philosophies.

Third, the inducted research trends and identified research hotspots portray the development of the PM field which facilitates to guide the direction and development of researchers and practitioners. In addition, upon analyzing the research content, limitations gradually appear in the existing body of knowledge, primarily in the incomplete coverage of research areas and the obvious separation of research themes, which need to be supplemented and enriched. Besides individual or team efforts, appropriate policies need to be formulated at the national and industry levels to guide and facilitate the development of such an interdisciplinary field and its corresponding industries.

In summary, a holistic and in-depth analysis of the objective nature of PM-related research has been conducted, and the resulting analysis contributes to a comprehensive understanding of PM field development, primarily in that (i) the underlying knowledge structure, current status, and research trends in the PM field are portrayed in detail by visualizing the PM knowledge pool, benefiting to capture objective PM field knowledge; (ii) hot topics in the PM field are systematically identified, enabling the reflection of the current and upcoming development of the PM field. In addition, research gaps in the field are revealed, which can guide the development both at the national level and at the industry level, including researchers and practitioners. This research contributes to the enrichment of the knowledge pool in the PM field and facilitates practical and research insights and guidance for researchers and practitioners conducting projects and industry development.

3.2. Research gaps in PM

Based on the previous analysis, this research adopts a systematic and quantitative bibliometric approach to clearly visualize and interpret PM knowledge from different perspectives, and applies inductive reasoning to integrate the hidden connections between knowledge bases, domains, and evolution to form a structured PM knowledge roadmap, as depicted in Figure 12. Despite the long-term growth of PM, many challenges exist in the wave of the times, along with the potential directions enabled by emerging technologies. Those are discussed below.

3.2.1. Policy challenges

LCA is a significant research theme in the quantitative evaluation of the factors involved in the life cycle for decision-making, where environmental factors are a vital consideration. It can assist in selecting maintenance elements with systematic concerns in PM (Santero et al., 2011a, 2011b). Given the findings above, environmental factors are becoming a global issue, thereby reducing material waste and energy consumption is of great interest to in-

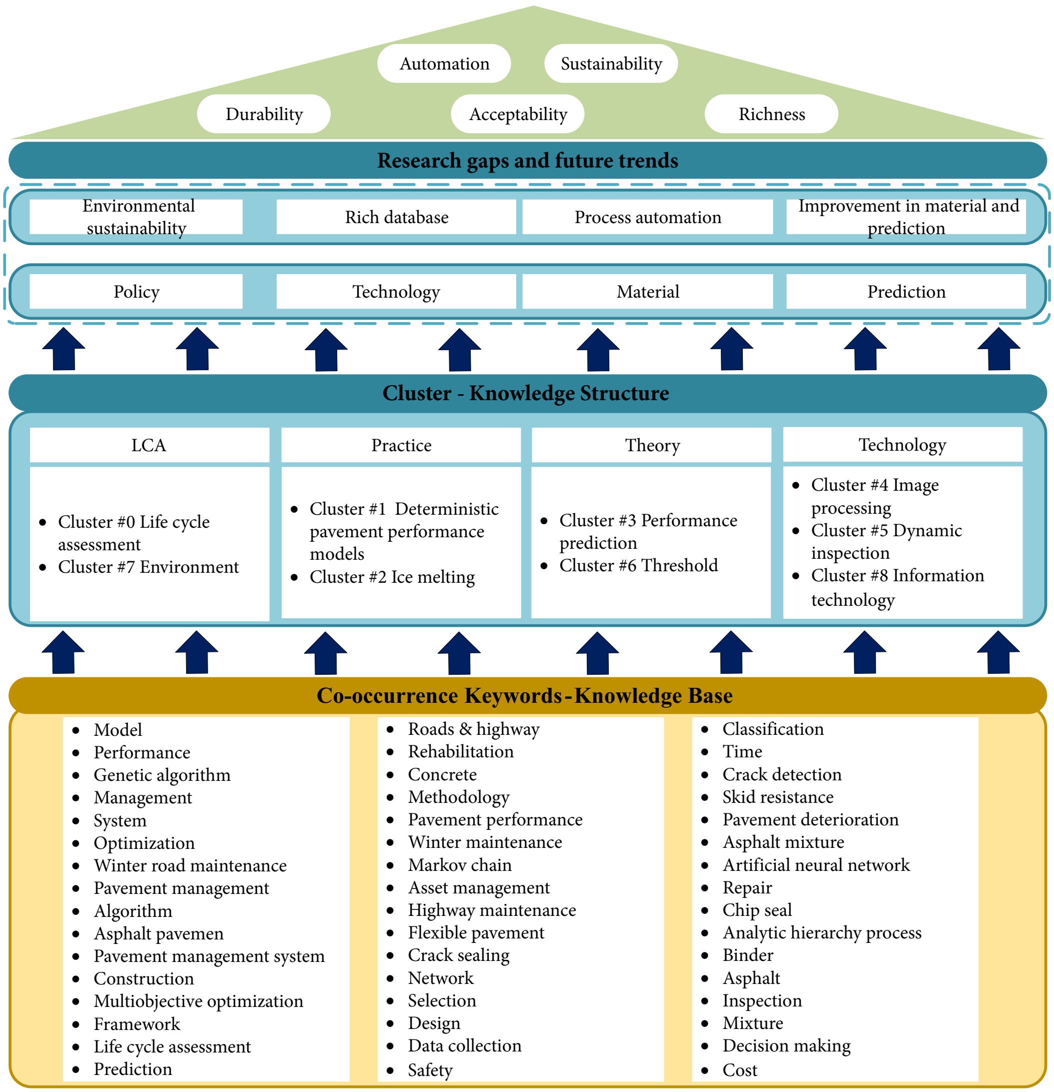

Figure 12. Knowledge roadmap of PM

dustry and academia (Yu & Lu, 2012). Policy instruments are crucial for improving energy efficiency, and reducing energy consumption through guidance and constraints, including the adoption of a series of legal measures and initiatives (Ruiz & Guevara, 2020). Nevertheless, it is challenging to develop practical policies with effective impact. That requires a global consensus from an inter-country perspective, which still suffers from weaknesses, providing a broad research horizon for academics. From an intra-country perspective, it will involve the adjustment of upstream and downstream industries, including technological upgrading and financial investment, which still has room for exploration with a long time.

3.2.2. Technology challenges

Technological innovation and application as a research theme in PM. Following clustering findings, image processing, dynamic inspection, and information technology are the most important methods employed in PM. However, advanced deep learning methods that come in with better accuracy and acceptability compared to classical machine learning methods, are in their infancy and will continue to be developed at the algorithm and system level, so as to be applicable to pavement conditions in various locations. In addition, those advanced technologies can be integrated into pavement management systems to facilitate the progress towards better pavement data processing for guiding PM, the integration of technologies and software, however, is a very challenging task, which may affect the performance of the whole system if not handled properly (Peraka & Biligiri, 2020). Moreover, numerous technologies are scattered in PM-related applications and are yet to break through the barriers to forming automated processes, which has room for improvement in terms of cost-effectiveness and time-efficiency. Furthermore, lots of algorithms need to be improved with the support of theoretical analysis, and the application and integration of numerous technologies need plenty of practice, but never an easy task for researchers and practitioners, which requires years of knowledge and experience accumulation, as well as team and even industry cooperation.

As the digital era pushes industries toward digitization and intelligence, artificial intelligence technology will play an important role in future PM research (Peraka & Biligiri, 2020). However, those methods are data-driven, requiring large amounts of data to enhance model performance, thus data collection becomes an essential part of PM to allow capture and analysis of pavement conditions in decision-making. In addition, facing intensive PM tasks and huge pavement networks, existing data collection methods restrict the application of advanced technologies and impose substantial manual workloads, such as image collection and processing.

3.2.3. Material challenges

As an essential element of PM, materials are related to the performance and service life of the pavement, and to the environment, climate, sustainability, etc. (Santos et al., 2015). Unfortunately, advances in pavement materials have not kept pace with progress in other advanced technologies, and little research has focused on this subfield, resulting in it has lagged behind the growth of the industry. In addition, the materials that have been utilized with concerns but little focus on sustainability, most of the materials are prone to polluting the environment and affecting the climate during the production or use of the materials, as well as not conducive to recycling (Chen & Zheng, 2021; Li et al., 2015). Moreover, the materials are mostly dependent on manual or semi-automated operations in the process of PM, restricting the mass application by considering cost-effectiveness and time-efficiency. Furthermore, materials research and practical application is a long, arduous, and challenging task that requires the unremitting efforts of researchers and practitioners involving cooperation and communication between industry and academia.

3.2.4. Prediction challenges

Pavement performance predictions over time can aid in management. To facilitate pavement management, the development of models for pavement performance prediction has been the research focus in the last two decades. The pavement prediction by the model assists the pavement management department to provide the best PM solution with the optimal benefit-cost ratio (Pérez-Acebo et al., 2018). However, because of the unclear interference and pavement operation process, along with the complex nature of the environment, predicting pavement performance remains an opportunity for exploration. In addition, there exists a decoupling between theory and practice. For example, performance models in the mechanistic-empirical pavement design guide (MEPDG), developed and calibrated from long-term pavement performance data, have been successfully applied to flexible and rigid pavements, however, differences exist when inputs such as climate, material properties, traffic patterns, and M&R methods (Pérez-Acebo et al., 2018; Waseem & Yuan, 2013). Moreover, no consensus has been reached on performance models due to numerous factors including limitations and uncertainty of pavement data, which is not conducive to the progress of PM.

3.3. Research trends in PM

Although the existing body of knowledge seems to cover all the major PM themes, rising topics within the field and potential collaborations among research clusters, and addressing those challenges of the identified knowledge gaps, can be regarded as the long-range future directions and industry adaptations for sustainable development.

3.3.1. Environmental sustainability

Studies in this direction primarily address policy and materials challenges. Policy development can contribute to the overall progress of PM in terms of environmental protection and increase awareness of environmental protection within the country, from departmental staff to grassroots workers, which can be awakened through increased advocacy. In addition, it requires an international organization for coordination to reach an international consensus on environmental protection to cover all areas, including PM. In developing policies, it is vital to fully capture the difficulties that exist for upstream and downstream businesses and industries related to PM, and then to develop targeted policies for environmental protection to promote sustainability.

In the meantime, a combination of compulsory and incentive measures should be implemented, with elements that have been identified as relevant to PM but serious to the environment being compulsorily closed, and some elements that are environmentally sound but less profitable being encouraged to be implemented. Additionally in the production of pavement materials, discarded construction materials can be mixed together into pavement materials for the application that satisfies the performance requirements, so as to reduce resource waste and realize environmental protection (Lu et al., 2019).

3.3.2. Rich database

Studies in this direction can involve addressing technical and prediction challenges. As data-driven methods, both the new-generation of information technology and prediction methods rely on the quality and quantity of data (Pan & Zhang, 2021; Pérez-Acebo et al., 2018). An extensive and high-quality database is a prerequisite to ensure the successful application of new-generation information technology or prediction models for PM. Therefore, a sufficiently sizable dataset needs to be built to ensure the performance of the next-generation information technology and prediction models applied to the PM. For the purpose, journal editors can require accepted papers for publication to provide the used data. In addition, encourage researchers to share their data voluntarily. Moreover, pavement management departments manage most of the pavement network, allowing the acquired pavement conditions to be recorded and shared in the management process. Furthermore, automated data collection should be developed along with technological advances.

Facing small datasets when applying deep learning techniques, the dataset can be extended using data augmentation techniques, such as rotation, flipping, and random cutting (Shorten & Khoshgoftaar, 2019; Taylor & Nitschke, 2019). Although not as rich as a real dataset, data augmentation techniques can alleviate the lack of data while improving model performance, contributing to the cost-effectiveness and time-efficiency of PM.

3.3.3. Process automation

This direction mainly addresses technical challenges. Automation is a practical, valuable direction that warrants devotion. Many advanced technologies have been introduced to describe the trend towards process automation of PM and to shape and enable automation development. The expected outcomes are increased execution efficiency, improved pavement quality, and lower maintenance costs through automation (Peraka & Biligiri, 2020). With real-time PM, an automation framework for an efficient and interconnected on-site platform can be developed based on the continuous advancement of automation technology. At the bottom of the framework lies the advanced technologies-supported functions/tasks, which provide decision support through the ongoing processing and analysis of data.

The intelligent PM management system (with a significant role) should be developed for assisting in the management of a pavement project; this could integrate various resources (e.g., visual sensors) and advanced technologies, such as smart robotics, virtual reality/augmented reality, 3D or 4D printing, digital twins, blockchain, etc. (Pan & Zhang, 2021) to obtain effective pavement information for data processing and analysis, thereby enabling contact and information acquisition and transmission among all stakeholders. Such a system could provide real-time feedback to assess pavement performance. To integrate technologies as well as break barriers, uniform technical protocols and operating rules are needed. Once the integration is achieved, the entire maintenance process can be simplified and the cost-effectiveness of the technology will improve.

3.3.4. Improvement in material and prediction

Studies in this direction can address material and prediction challenges. With the aim to improve pavement performance in terms of durability and serviceability of the pavement, new materials can be developed or the material's performance can be improved. As previously discussed in sustainability, discarded construction waste can be mixed into the material to improve its utilization while maintaining performance (Lu et al., 2019). In addition, the new materials need to be developed along with the application of new technologies for PM, such as printing technology that requires pavement materials to have good a flow with efficient coagulation. Furthermore, the durability of pavement materials needs to be improved to increase the service life of the pavement, such as adding steel fibre (Murthi et al., 2020), granite, aluminum, silicon, etc. (Busang & Maina, 2022) to the material.

In the long-term PM horizon, assessing pavement performance is a basic and important step. It is significant to build a model with broad acceptance. This requires the model to be able to effectively extract information while identifying uncertainty and eliminating interference. In pavement condition prediction, the commonly used method is Markov chains for pavement condition assessment, thus improvements can be made to the model based on the practical to make it better suited to the application, such as the semi-Markov model (Thomas & Sobanjo, 2013). In addition, machine learning has proven to be powerful for prediction, so that it can be applied to pavement condition prediction, such as ANN, support vector machines, automatic machine learning, etc. (Kargah-Ostadi & Stoffels, 2015). Moreover, various countries and some organizations have developed many models for pavement assessment, such as HDM-4 (Thube, 2013) and MEPDG (Waseem & Yuan, 2013), upon which the advantages of those models can be taken into account to propose models with widespread consensus and high accuracy to be promoted and applied on PM.

In light of the analysis, an important point is to strengthen the extensive communication and in-depth exchange between industry and academia of PM for sharing knowledge and application of advanced products, so as to form the development pain points and needs of the industry to drive the focus and research of academia, thereby in turn acting on industry to constitute a sound working with technical support and the coexistence of industry and academia, enriching the domain knowledge pool and promoting industry progress.

Conclusions

PM is attracting increasing amounts of attention from researchers and practitioners. A scientometric-assisted review was conducted to explore and visualize the research status quo through author analysis, spatial distribution analysis, keyword analysis, and document analysis based on the 614 articles published from 2001 to 2020 in the WoS database. Those analyses can provide researchers and practitioners with an in-depth understanding of PM research and identify emerging trends to support future studies. Additionally for the published articles, it is apparent that the publications in the PM field have a significant increase, especially since 2013, indicating that PM is a traditional and everlasting research domain that is being updated with new elements (e.g., deep learning, information technology).

In view of the analysis results, several conclusions can be summarized as follows. (1) Communication and collaboration among authors have formed several communities for knowledge sharing, in which many influential authors such as Zhanming Zhang, Alfredas Laurinavicius, and Adelino Ferreira play a key role, most of the authors, however, were isolated. It is also found that the research of TienFang Fwa and Ralph Haas has gained a lot of influence to be learned by many researchers thus contributing favorably to the field's development. (2) Compared to the numerous research institutions and countries, presence in the network is limited, indicating that neither institutions nor countries have formed broad communication and cooperation. In the country networks, the majority are developed countries, while developing countries still have much room to enhance communication and cooperation with mainstream countries for globalization by removing barriers. (3) Keyword analysis reveals the mainstream topics in the PM field, including model, performance, management, system, and optimization, and they have been continuously evolving in these two decades. Additionally, attention, in recent years, has focused on the application of information technology, especially deep learning, etc. The continuous efforts on PM strategy development indeed strengthen pavement maintenance from the management aspect, in addition to increasing investment in technology to enable technology-supported development. (4) The documents form several communities, within which most of the citations occur, while only a few communities have sparse or even no connections, blocking the intersection of different theories and ideas, thus strengthening the extensive coverage of research subfields that should be given attention. The documents to clusters based on the keywords reveal prominent research themes, which involve research directions that have become hot, including LCA, deterministic pavement performance models, ice melting, performance prediction, image processing, dynamic detection, etc. Those could provide the optimal combination to improve PM. More importantly, scientometric-assisted analysis crystallized valuable and key findings of PM-related ontology research that can provide significant information to researchers and industry practitioners about the current lack of initiative within the field and offer insights for future research directions that can focus on the challenges presented in this research.

Much effort has been made to review important developments in PM, but not exhaustive with potential for improvement. For example, future studies could be conducted to cover the full scope for the review, including conference papers. In addition, the selected research literature sample in the dataset is from Web of Science, which can be extended to include Scopus. Moreover, the knowledge revealed about PM represents the current status, while PM research is a rapidly expanding field of study and highly multi-disciplinary, the knowledge related to PM may change in the future, integrating future changes, thus, is necessary for further capturing the latest body of knowledge regarding PM.

Acknowledgements

This research was supported by the National Social Science Fund of China (No. 18ZDA043).

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the manuscript.

References

Abaza, K. A. (2005). Performance-based models for flexible pavement structural overlay design. *Journal of Transportation Engineering*, *131*(2), 149–159. https://doi.org/10.1061/(ASCE)0733-947X(2005)131:2(149)

Abaza, K. A. (2016). Back-calculation of transition probabilities for markovian-based pavement performance prediction models. *International Journal of Pavement Engineering*, *17*(3), 253–264. https://doi.org/10.1080/10298436.2014.993185

Abaza, K. A., Ashur, S. A., & Al-Khatib, I. A. (2004). Integrated pavement management system with a Markovian prediction model. *Journal of Transportation Engineering*, *130*(1), 24–33. https://doi.org/10.1061/(ASCE)0733-947X(2004)130:1(24)

Abotaleb, I. S., & El-adaway, I. H. (2018). Managing construction projects through dynamic modeling: Reviewing the existing body of knowledge and deriving future research directions. *Journal of Management in Engineering*, *34*(6), 04018033. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000633

Ahmed, K., Al-Khateeb, B., & Mahmood, M. (2019). Application of chaos discrete particle swarm optimization algorithm on pavement maintenance scheduling problem. *Cluster Computing*, *22*(Suppl 2), 4647–4657. https://doi.org/10.1007/s10586-018-2239-3

Amin, S., Tamima, U., & Amador-Jiménez, L. E. (2019). Optimal pavement management: Resilient roads in support of emergency response of cyclone affected coastal areas. *Transportation Research Part A: Policy and Practice*, *119*, 45–61. https://doi.org/10.1016/j.tra.2018.11.001

Bang, S., Park, S., Kim, H., & Kim, H. (2019). Encoder–decoder network for pixel-level road crack detection in black-box images. *Computer-Aided Civil and Infrastructure Engineering*, *34*(8), 713–727. https://doi.org/10.1111/mice.12440

Bayer, A. E., Smart, J. C., & McLaughlin, G. W. (1990). Mapping intellectual structure of a scientific subfield through author cocitations. *Journal of the American Society for Information Science*, *41*(6), 444–452. https://doi.org/10.1002/(SICI)1097-4571(199009)41:6<444::AID-ASI12>3.0.CO;2-J

Bosurgi, G., & Trifirò, F. (2005). A model based on artificial neural networks and genetic algorithms for pavement maintenance management. *International Journal of Pavement Engineering*, *6*(3), 201–209. https://doi.org/10.1080/10298430500195432

Bressi, S., Dumont, A. G., & Partl, M. N. (2016). A new laboratory methodology for optimization of mixture design of asphalt concrete containing reclaimed asphalt pavement material. *Materials and Structures*, *49*(12), 4975–4990. https://doi.org/10.1617/s11527-016-0837-1

Busang, S., & Maina, J. (2022). Influence of aggregates properties on microstructural properties and mechanical performance of asphalt mixtures. *Construction and Building Materials*, *318*, 126002. https://doi.org/10.1016/j.conbuildmat.2021.126002

Butler, L., & Visser, M. S. (2006). Extending citation analysis to non-source items. *Scientometrics*, *66*(2), 327–343. https://doi.org/10.1007/s11192-006-0024-1

Cha, Y. J., Choi, W., & Büyüköztürk, O. (2017). Deep learning-based crack damage detection using convolutional neural networks. *Computer-Aided Civil and Infrastructure Engineering*, *32*(5), 361–378. https://doi.org/10.1111/mice.12263

Chang, J. R. (2013). Particle swarm optimization method for optimal prioritization of pavement sections for maintenance and rehabilitation activities. *Applied Mechanics and Materials*, *343*, 43–49. https://doi.org/10.4028/www.scientific.net/amm.343.43

Chen, C. (2004). Searching for intellectual turning points: Progressive knowledge domain visualization. *Proceedings of the National Academy of Sciences of the United States of America*, *101*, 5303–5310. https://doi.org/10.1073/pnas.0307513100

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, *57*(3), 359–377. https://doi.org/10.1002/asi.20317

Chen, C. (2017). Science mapping: A systematic review of the literature. *Journal of Data and Information Science*, *2*(2), 1–40. https://doi.org/10.1515/jdis-2017-0006

Chen, C., Ibekwe-SanJuan, F., & Hou, J. (2010). The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. *Journal of the American Society for Information Science and Technology*, *61*(7), 1386–1409. https://doi.org/10.1002/asi.21309

Chen, C., & Morris, S. (2003). Visualizing evolving networks: Minimum spanning trees versus Pathfinder networks. In *Proceedings of IEEE Symposium on Information Visualization* (*INFO VIS*) (pp. 67–74). https://doi.org/10.1109/INFVIS.2003.1249010

Chen, W., & Zheng, M. (2021). Multi-objective optimization for pavement maintenance and rehabilitation decision-making: A critical review and future directions. *Automation in Construction*, *130*, 103840. https://doi.org/10.1016/j.autcon.2021.103840

Chootinan, P., Chen, A., Horrocks, M. R., & Bolling, D. (2006). A multi-year pavement maintenance program using a stochastic simulation-based genetic algorithm approach. *Transportation Research Part A: Policy and Practice*, *40*(9), 725–743. https://doi.org/10.1016/j.tra.2005.12.003

Chou, J. S., & Le, T. S. (2011). Reliability-based performance simulation for optimized pavement maintenance. *Reliability Engineering and System Safety*, *96*(10), 1402–1410. https://doi.org/10.1016/j.ress.2011.05.005

Chupin, O., Piau, J. M., & Chabot, A. (2013). Evaluation of the structure-induced rolling resistance (SRR) for pavements including viscoelastic material layers. *Materials and Structures*, *46*(4), 683–696. https://doi.org/10.1617/s11527-012-9925-z

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). Science mapping software tools: Review, analysis, and cooperative study among tools. *Journal of the American Society for Information Science and Technology*, *62*(7), 1382–1402. https://doi.org/10.1002/asi.21525

Coenen, T. B. J., & Golroo, A. (2017). A review on automated pavement distress detection methods. *Cogent Engineering*, *4*(1), 1374822. https://doi.org/10.1080/23311916.2017.1374822

de la Garza, J. M., Akyildiz, S., Bish, D. R., & Krueger, D. A. (2011). Network-level optimization of pavement maintenance renewal strategies. *Advanced Engineering Informatics*, *25*(4), 699–712. https://doi.org/10.1016/j.aei.2011.08.002

de Souza, N. M., & de Almeida Filho, A. T. (2020). A systematic airport runway maintenance and inspection policy based on a delay time modeling approach. *Automation in Construction*, *110*, 103039. https://doi.org/10.1016/j.autcon.2019.103039

Ding, Y. (2011). Scientific collaboration and endorsement: Network analysis of coauthorship and citation networks. *Journal of Informetrics*, *5*(1), 187–203. https://doi.org/10.1016/j.joi.2010.10.008

Dong, Q., Huang, B., Richards, S. H., & Yan, X. (2013). Cost-effectiveness analyses of maintenance treatments for low- and moderate-traffic asphalt pavements in Tennessee. *Journal of Transportation Engineering*, *139*(8), 797–803. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000556

El-adaway, I. H., Ali, G., Assaad, R., Elsayegh, A., & Abotaleb, I. S. (2019). Analytic overview of citation metrics in the civil engineering domain with focus on construction engineering and management specialty area and its subdisciplines. *Journal of Construction Engineering and Management*, *145*(10), 04019060. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001705

Elhadidy, A. A., Elbeltagi, E. E., & Ammar, M. A. (2015). Optimum analysis of pavement maintenance using multi-objective genetic algorithms. *HBRC Journal*, *11*(1), 107–113. https://doi.org/10.1016/j.hbrcj.2014.02.008

Fay, L., & Shi, X. (2012). Environmental impacts of chemicals for snow and ice control: State of the knowledge. *Water*, *Air*, *and Soil Pollution*, *223*(5), 2751–2770. https://doi.org/10.1007/s11270-011-1064-6

France-Mensah, J., & O'Brien, W. J. (2019). Developing a sustainable pavement management plan: tradeoffs in road condition, user costs, and greenhouse gas emissions. *Journal of Management in Engineering*, *35*(3), 04019005. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000686

Fu, Z., Shen, W., Huang, Y., Hang, G., & Li, X. (2017). Laboratory evaluation of pavement performance using modified asphalt mixture with a new composite reinforcing material. *International Journal of Pavement Research and Technology*, *10*(6), 507–516. https://doi.org/10.1016/j.ijprt.2017.04.001

Gao, H., & Zhang, X. (2013). A markov-based road maintenance optimization model considering user costs. *Computer-Aided Civil and Infrastructure Engineering*, *28*(6), 451–464. https://doi.org/10.1111/mice.12009

Giustozzi, F., Crispino, M., & Flintsch, G. (2012). Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability. *International Journal of Life Cycle Assessment*, *17*(4), 409–419. https://doi.org/10.1007/s11367-011-0375-6

Gopalakrishnan, K., Khaitan, S. K., Choudhary, A., & Agrawal, A. (2017). Deep convolutional neural networks with transfer learning for computer vision-based data-driven pavement distress detection. *Construction and Building Materials*, *157*, 322–330. https://doi.org/10.1016/j.conbuildmat.2017.09.110

Gosse, C. A., Smith, B. L., & Clarens, A. F. (2013). Environmentally preferable pavement management systems. *Journal of Infrastructure Systems*, *19*(3), 315–325. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000118

Hess, D. J. (1997). *Science studies: An advanced introduction*. NYU Press.

Hoang, N.-D., Nguyen, Q. L., & Tran, V. D. (2018). Automatic recognition of asphalt pavement cracks using metaheuristic optimized edge detection algorithms and convolution neural network. *Automation in Construction*, *94*, 203–213. https://doi.org/10.1016/j.autcon.2018.07.008

Hoang, N. D. (2019). Image processing based automatic recognition of asphalt pavement patch using a metaheuristic optimized machine learning approach. *Advanced Engineering Informatics*, *40*, 110–120. https://doi.org/10.1016/j.aei.2019.04.004

Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., & Chileshe, N. (2018). Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in Construction*, *87*, 235–247. https://doi.org/10.1016/j.autcon.2017.12.002

Huang, J., Liu, W., & Sun, X. (2014). A pavement crack detection method combining 2D with 3D information based on dempster-shafer theory. *Computer-Aided Civil and Infrastructure Engineering*, *29*(4), 299–313. https://doi.org/10.1111/mice.12041

Huang, Y., Bird, R., & Bell, M. (2009). A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. *Transportation Research Part D: Transport and Environment*, *14*(3), 197–204. https://doi.org/10.1016/j.trd.2008.12.003

Inzerillo, L., Di Mino, G., & Roberts, R. (2018). Image-based 3D reconstruction using traditional and UAV datasets for analysis of road pavement distress. *Automation in Construction*, *96*, 457–469. https://doi.org/10.1016/j.autcon.2018.10.010

Ji, A., Xue, X., Wang, Y., Luo, X., & Xue, W. (2020). An integrated approach to automatic pixel-level crack detection and quantification of asphalt pavement. *Automation in Construction*, *114*, 103176. https://doi.org/10.1016/j.autcon.2020.103176

Jo, Y., & Ryu, S. (2015). Pothole detection system using a blackbox camera. *Sensors*, *15*(11), 29316–29331. https://doi.org/10.3390/s151129316

Johannesson, P., Podgórski, K., & Rychlik, I. (2016). Modelling roughness of road profiles on parallel tracks using roughness indicators. *International Journal of Vehicle Design*, *70*(2), 183–210. https://doi.org/10.1504/IJVD.2016.074421

Jorge, D., & Ferreira, A. (2012). Road network pavement maintenance optimisation using the HDM-4 pavement performance prediction models. *International Journal of Pavement Engineering*, *13*(1), 39–51. https://doi.org/10.1080/10298436.2011.563851

Kargah-Ostadi, N., & Stoffels, S. M. (2015). Framework for development and comprehensive comparison of empirical pavement performance models. *Journal of Transportation Engineering*, *141*(8), 04015012. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000779

Khahro, S. H., Memon, Z. A., Nur, N. I., Gungat, L., & Yazid, M. R. M. (2020). Pavement management system research output: A scientometric assessment. *Library Philosophy and Practice - Electronic Journal*, *2020*, 4145.

Khan, M. U., Mesbah, M., Ferreira, L., & Williams, D. J. (2014). Developing a new road deterioration model incorporating flooding. *Proceedings of the Institution of Civil Engineers – Transport*, *167*(5), 322–333. https://doi.org/10.1680/tran.13.00095

Kim, B., & Cho, S. (2019). Image-based concrete crack assessment using mask and region-based convolutional neural network. *Structural Control and Health Monitoring*, *26*(8), e2381. https://doi.org/10.1002/stc.2381

Kobayashi, K., Do, M., & Han, D. (2010). Estimation of markovian transition probabilities for pavement deterioration forecasting. *KSCE Journal of Civil Engineering*, *14*(3), 343–351. https://doi.org/10.1007/s12205-010-0343-x

Koch, C., Jog, G. M., & Brilakis, I. (2013). Automated pothole distress assessment using asphalt pavement video data. *Journal of Computing in Civil Engineering*, *27*(4), 370–378. https://doi.org/10.1061/(asce)cp.1943-5487.0000232

Lee, J., & Madanat, S. (2017). Optimal policies for greenhouse gas emission minimization under multiple agency budget constraints in pavement management. *Transportation Research Part D: Transport and Environment*, *55*, 39–50. https://doi.org/10.1016/j.trd.2017.06.009

Lee, J., Madanat, S., & Reger, D. (2016). Pavement systems reconstruction and resurfacing policies for minimization of life-cycle costs under greenhouse gas emissions constraints. *Transportation Research Part B: Methodological*, *93*, 618–630. https://doi.org/10.1016/j.trb.2016.08.016

Lethanh, N., & Adey, B. T. (2013). Use of exponential hidden markov models for modelling pavement deterioration. *International Journal of Pavement Engineering*, *14*(7), 645–654. https://doi.org/10.1080/10298436.2012.715647

Li, H., Harvey, J., & Huang, X. (2015). Moving towards a sustainable transportation system: Focus issue on sustainable transportation technology and policy. *International Journal of Transportation Science and Technology*, *4*(1), III–VIII. https://doi.org/10.1260/2046-0430.4.1.iii

Li, Z., Cheng, C., Kwan, M. P., Tong, X., & Tian, S. (2019). Identifying asphalt pavement distress using UAV LiDAR point cloud data and random forest classification. *ISPRS International Journal of Geo-Information*, *8*(1), 39. https://doi.org/10.3390/ijgi8010039

Lidicker, J., Sathaye, N., Madanat, S., & Horvath, A. (2013). Pavement resurfacing policy for minimization of life-cycle costs and greenhouse gas emissions. *Journal of Infrastructure Systems*, *19*(2), 129–137. https://doi.org/10.1061/(asce)is.1943-555x.0000114

Lu, G., Liu, P., Wang, Y., Faßbender, S., Wang, D., & Oeser, M. (2019). Development of a sustainable pervious pavement material using recycled ceramic aggregate and bio-based polyurethane binder. *Journal of Cleaner Production*, *220*, 1052–1060. https://doi.org/10.1016/j.jclepro.2019.02.184

Lu, H., & Feng, Y. (2009). A measure of authors' centrality in co-authorship networks based on the distribution of collaborative relationships. *Scientometrics*, *81*(2), 499–511. https://doi.org/10.1007/s11192-008-2173-x

Luo, T., Tan, Y., Langston, C., & Xue, X. (2019). Mapping the knowledge roadmap of low carbon building: A scientometric analysis. *Energy and Buildings*, *194*, 163–176. https://doi.org/10.1016/j.enbuild.2019.03.050

Luwel, M. (2004). The use of input data in the performance analysis of R&D systems. In *Handbook of quantitative science and technology research* (pp. 315–338). Springer. https://doi.org/10.1007/1-4020-2755-9_15

Ma, J., Cheng, L., & Li, D. (2018). Road maintenance optimization model based on dynamic programming in Urban traffic network. *Journal of Advanced Transportation*, *2018*, 4539324. https://doi.org/10.1155/2018/4539324

Maeda, H., Sekimoto, Y., Seto, T., Kashiyama, T., & Omata, H. (2018). Road damage detection and classification using deep neural networks with smartphone images. *Computer-Aided Civil and Infrastructure Engineering*, *33*(12), 1127–1141. https://doi.org/10.1111/mice.12387

Marcelino, P., de Lurdes Antunes, M., Fortunato, E., & Gomes, M. C. (2021). Machine learning approach for pavement performance prediction. *International Journal of Pavement Engineering*, *22*(3), 341–354. https://doi.org/10.1080/10298436.2019.1609673

Martinez, P., Al-Hussein, M., & Ahmad, R. (2019). A scientometric analysis and critical review of computer vision applications for construction. *Automation in Construction*, *107*, 102947. https://doi.org/10.1016/j.autcon.2019.102947

Mathew, B. S., & Isaac, K. P. (2014). Optimisation of maintenance strategy for rural road network using genetic algorithm. *International Journal of Pavement Engineering*, *15*(4), 352–360. https://doi.org/10.1080/10298436.2013.806807

Morcous, G., & Lounis, Z. (2005). Maintenance optimization of infrastructure networks using genetic algorithms. *Automation in Construction*, *14*(1), 129–142. https://doi.org/10.1016/j.autcon.2004.08.014

Múčka, P. (2013). Correlation among road unevenness indicators and vehicle vibration response. *Journal of Transportation Engineering*, *139*(8), 771–786. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000558

Murthi, P., Poongodi, K., & Gobinath, R. (2020). Correlation between rebound hammer number and mechanical properties of steel fibre reinforced pavement quality concrete. *Materials Today: Proceedings*, *39*, 142–147. https://doi.org/10.1016/j.matpr.2020.06.402

Newman, M. E. J. (2006). Modularity and community structure in networks. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(23), 8577–8582. https://doi.org/10.1073/pnas.0601602103

Ng, M. W., Lin, D. Y., & Waller, S. T. (2009). Optimal long-term infrastructure maintenance planning accounting for traffic dynamics. *Computer-Aided Civil and Infrastructure Engineering*, *24*(7), 459–469. https://doi.org/10.1111/j.1467-8667.2009.00606.x

Ni, F. T., Zhang, J., & Chen, Z. Q. (2019). Zernike-moment measurement of thin-crack width in images enabled by dual-scale deep learning. *Computer-Aided Civil and Infrastructure Engineering*, *34*(5), 367–384. https://doi.org/10.1111/mice.12421

O'Flaherty, C., & Hughes, D. (2015). *Highways: The location, design, construction and maintenance of road pavements* (15th ed.). https://doi.org/10.1680/h5e.59931

Olawumi, T. O., & Chan, D. W. M. (2018). A scientometric review of global research on sustainability and sustainable development. *Journal of Cleaner Production*, *183*, 231–250. https://doi.org/10.1016/j.jclepro.2018.02.162

Ouma, Y. O., & Hahn, M. (2016). Wavelet-morphology based detection of incipient linear cracks in asphalt pavements from RGB camera imagery and classification using circular Radon transform. *Advanced Engineering Informatics*, *30*(3), 481–499. https://doi.org/10.1016/j.aei.2016.06.003

Outay, F., Mengash, H. A., & Adnan, M. (2020). Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: Recent advances and challenges. *Transportation Research Part A: Policy and Practice*, *141*, 116–129. https://doi.org/10.1016/j.tra.2020.09.018

Ouyang, Y., & Madanat, S. (2004). Optimal scheduling of rehabilitation activities for multiple pavement facilities: Exact and approximate solutions. *Transportation Research Part A: Policy and Practice*, *38*(5), 347–365. https://doi.org/10.1016/j.tra.2003.10.007

Ouyang, Y., & Madanat, S. (2006). An analytical solution for the finite-horizon pavement resurfacing planning problem. *Transportation Research Part B: Methodological*, *40*(9), 767–778. https://doi.org/10.1016/j.trb.2005.11.001

Ozbek, M. E., de la Garza, J. M., & Triantis, K. (2010). Data and modeling issues faced during the efficiency measurement of road maintenance using data evelopment analysis. *Journal of Infrastructure Systems*, *16*(1), 21–30. https://doi.org/10.1061/(asce)1076-0342(2010)16:1(21)

Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction*, *122*, 103517. https://doi.org/10.1016/j.autcon.2020.103517

Peraka, N. S. P., & Biligiri, K. P. (2020). Pavement asset management systems and technologies: A review. *Automation in Construction*, *119*, 103336. https://doi.org/10.1016/j.autcon.2020.103336

Pérez-Acebo, H., Linares-Unamunzaga, A., Abejón, R., & Rojí, E. (2018). Research trends in pavement management during the first years of the 21st century: A bibliometric analysis during the 2000-2013 Period. *Applied Sciences*, *8*(7), 1041. https://doi.org/10.3390/app8071041

Prozzi, J. A., & Madanat, S. M. (2003). Incremental nonlinear model for predicting pavement serviceability. *Journal of Transportation Engineering*, *129*(6), 635–641. https://doi.org/10.1061/(ASCE)0733-947X(2003)129:6(635)

Ruiz, A., & Guevara, J. (2020). Environmental and economic impacts of road infrastructure development: Dynamic considerations and policies. *Journal of Management in Engineering*, *36*(3), 04020006. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000755

Saberian, M., Li, J., & Setunge, S. (2019). Evaluation of permanent deformation of a new pavement base and subbase containing unbound granular materials, crumb rubber and crushed glass. *Journal of Cleaner Production*, *230*, 38–45. https://doi.org/10.1016/j.jclepro.2019.05.100

Saha, P., Liu, R., Melson, C., & Boyles, S. D. (2014). Network model for rural roadway tolling with pavement deterioration and repair. *Computer-Aided Civil and Infrastructure Engineering*, *29*(5), 315–329. https://doi.org/10.1111/mice.12057

Sánchez-Silva, M., Frangopol, D. M., Padgett, J., & Soliman, M. (2016). Maintenance and operation of infrastructure systems: Review. *Journal of Structural Engineering*, *142*(9), F4016004. https://doi.org/10.1061/(asce)st.1943-541x.0001543

Santero, N. J. (2009). *Pavements and the environment: a life-cycle assessment approach*. University of California, Berkeley.

Santero, N. J., Masanet, E., & Horvath, A. (2011a). Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling*, *55*(9–10), 801–809. https://doi.org/10.1016/j.resconrec.2011.03.010

Santero, N. J., Masanet, E., & Horvath, A. (2011b). Life-cycle assessment of pavements Part II: Filling the research gaps. *Resources, Conservation and Recycling*, *55*(9–10), 810–818. https://doi.org/10.1016/j.resconrec.2011.03.009

Santos, J., Ferreira, A., & Flintsch, G. (2015). A life cycle assessment model for pavement management: Methodology and computational framework. *International Journal of Pavement Engineering*, *16*(3), 268–286. https://doi.org/10.1080/10298436.2014.942861

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. https://doi.org/10.1016/j.jclepro.2017.07.027

Sarsam, S. I. (2016). Pavement maintenance management system: A review. *Trends in Transport Engineering and Applications*, *3*(2), 19–30.

Settari, C., Debieb, F., Kadri, E. H., & Boukendakdji, O. (2015). Assessing the effects of recycled asphalt pavement materials on the performance of roller compacted concrete. *Construction and Building Materials*, *101*, 617–621. https://doi.org/10.1016/j.conbuildmat.2015.10.039

Shi, X., Veneziano, D., Xie, N., & Gong, J. (2013). Use of chloride-based ice control products for sustainable winter maintenance: A balanced perspective. *Cold Regions Science and Technology*, *86*, 104–112. https://doi.org/10.1016/j.coldregions.2012.11.001

Shorten, C., & Khoshgoftaar, T. M. (2019). A survey on image data augmentation for deep learning. *Journal of Big Data*, *6*, 60. https://doi.org/10.1186/s40537-019-0197-0

Sivilevičius, H., & Vansauskas, V. (2013). Research and evaluation of ruts in the asphalt pavement on Lithuanian highways. *Journal of Civil Engineering and Management*, *19*(5), 609–621. https://doi.org/10.3846/13923730.2013.817481

Statista. (2021). *Total length of public roads in China from 2008 to 2020*. https://www.statista.com/statistics/276051/total-length-of-public-roads-in-china/

Sultana, M., Rahman, A., & Chowdhury, S. (2013). A review of performance based maintenance of road infrastructure by contracting. *International Journal of Productivity and Performance Management*, *62*(3), 276–292. https://doi.org/10.1108/17410401311309186

Sun, X., Gao, Z., Cao, P., & Zhou, C. (2019). Mechanical properties tests and multiscale numerical simulations for basalt fiber reinforced concrete. *Construction and Building Materials*, *202*, 58–72. https://doi.org/10.1016/j.conbuildmat.2019.01.018

Suresh, K., & Kumarappan, N. (2013). Hybrid improved binary particle swarm optimization approach for generation maintenance scheduling problem. *Swarm and Evolutionary Computation*, *9*, 69–89. https://doi.org/10.1016/j.swevo.2012.11.003

Taylor, L., & Nitschke, G. (2019). Improving deep learning with generic data augmentation. In *Proceedings of the 2018 IEEE Symposium Series on Computational Intelligence* (*SSCI 2018*) (pp. 1542–1547). https://doi.org/10.1109/SSCI.2018.8628742

Tehrani, S. S., Cowe Falls, L., & Mesher, D. (2015). Road users' perception of roughness and the corresponding IRI threshold values. *Canadian Journal of Civil Engineering*, *42*(4), 233–240. https://doi.org/10.1139/cjce-2014-0344

Thomas, O., & Sobanjo, J. (2013). Comparison of markov chain and semi-markov models for crack deterioration on flexible pavements. *Journal of Infrastructure Systems*, *19*(2), 186–195. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000112

Thube, D. T. (2013). Highway development and management model (HDM-4): Calibration and adoption for low-volume roads in local conditions. *International Journal of Pavement Engineering*, *14*(1), 50–59. https://doi.org/10.1080/10298436.2011.606320

TRIP. (2022). *America's surface transportation system and federal funding key facts*. https://tripnet.org/wp-content/uploads/2019/05/Fact_Sheet_National.pdf

Tuttle, R. S. (2005). *Condition analysis of concrete bridge decks in Utah*. https://scholarsarchive.byu.edu/etd/567

Van Noortwijk, J. M., & Frangopol, D. M. (2004). Two probabilistic life-cycle maintenance models for deteriorating civil infrastructures. *Probabilistic Engineering Mechanics*, *19*(4), 345–359. https://doi.org/10.1016/j.probengmech.2004.03.002

Vaneman, W. K., & Triantis, K. (2007). Evaluating the productive efficiency of dynamical systems. *IEEE Transactions on Engineering Management*, *54*(3), 600–612. https://doi.org/10.1109/TEM.2007.900798

Vázquez-Méndez, M. E., Casal, G., Santamarina, D., & Castro, A. (2018). A 3D model for optimizing infrastructure costs in road design. *Computer-Aided Civil and Infrastructure Engineering*, *33*(5), 423–439. https://doi.org/10.1111/mice.12350

Vyas, V., Singh, A. P., & Srivastava, A. (2021). Entropy-based fuzzy SWOT decision-making for condition assessment of airfield pavements. *International Journal of Pavement Engineering*, *22*(10), 1226–1237. https://doi.org/10.1080/10298436.2019.1671590

Wang, J. (2013). Citation time window choice for research impact evaluation. *Scientometrics*, *94*(3), 851–872. https://doi.org/10.1007/s11192-012-0775-9

Wang, H., & Wang, Z. (2013). Evaluation of pavement surface friction subject to various pavement preservation treatments. *Construction and Building Materials*, *48*, 194–202. https://doi.org/10.1016/j.conbuildmat.2013.06.048

Wang, H., Al-Saadi, I., Lu, P., & Jasim, A. (2020). Quantifying greenhouse gas emission of asphalt pavement preservation at construction and use stages using life-cycle assessment. *International Journal of Sustainable Transportation*, *14*(1), 25–34. https://doi.org/10.1080/15568318.2018.1519086

Waseem, A., & Yuan, X. X. (2013). Longitudinal local calibration of MEPDG permanent deformation models for reconstructed flexible pavements using PMS data. *International Journal of Pavement Research and Technology*, *6*(4), 304–312.

Wu, W., Qurishee, M. A., Owino, J., Fomunung, I., Onyango, M., & Atolagbe, B. (2019). Coupling deep learning and UAV for infrastructure condition assessment automation. In *2018 IEEE International Smart Cities Conference* (*ISC2 2018*), Kansas City, MO, USA. https://doi.org/10.1109/ISC2.2018.8656971

Wu, Z., Flintsch, G., Ferreira, A., & de Picado-Santos, L. (2012). Framework for multiobjective optimization of physical highway assets investments. *Journal of Transportation Engineering*, *138*(12), 1411–1421. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000458

Wu, Z., & Flintsch, G. W. (2009). Pavement preservation optimization considering multiple objectives and budget variability. *Journal of Transportation Engineering*, *135*(5), 305–315. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000006

Xinhua. (2013). China issues plan for national road network. *Chinadaily*. http://www.chinadaily.com.cn/china/2013-06/20/content_16641094.htm

Yang, X., Li, H., Yu, Y., Luo, X., Huang, T., & Yang, X. (2018). Automatic pixel-level crack detection and measurement using fully convolutional network. *Computer-Aided Civil and Infrastructure Engineering*, *33*(12), 1090–1109. https://doi.org/10.1111/mice.12412

Yao, L., Dong, Q., Jiang, J., & Ni, F. (2020). Deep reinforcement learning for long-term pavement maintenance planning. *Computer-Aided Civil and Infrastructure Engineering*, *35*(11), 1230–1245. https://doi.org/10.1111/mice.12558

Yepes, V., Torres-Machi, C., Chamorro, A., & Pellicer, E. (2016). Optimal pavement maintenance programs based on a hybrid Greedy Randomized Adaptive Search Procedure Algorithm. *Journal of Civil Engineering and Management*, *22*(4), 540–550. https://doi.org/10.3846/13923730.2015.1120770

Yousaf, M. H., Azhar, K., Murtaza, F., & Hussain, F. (2018). Visual analysis of asphalt pavement for detection and localization of potholes. *Advanced Engineering Informatics*, *38*, 527–537. https://doi.org/10.1016/j.aei.2018.09.002

Yu, B., Gu, X., Ni, F., & Guo, R. (2015). Multi-objective optimization for asphalt pavement maintenance plans at project level: Integrating performance, cost and environment. *Transportation Research Part D: Transport and Environment*, *41*, 64–74. https://doi.org/10.1016/j.trd.2015.09.016

Yu, B., Guo, Z., Peng, Z., Wang, H., Ma, X., & Wang, Y. (2019). Agent-based simulation optimization model for road surface maintenance scheme. *Journal of Transportation Engineering, Part B: Pavements*, *145*(1), 04018065. https://doi.org/10.1061/jpeodx.0000097

Yu, B., & Lu, Q. (2012). Life cycle assessment of pavement: Methodology and case study. *Transportation Research Part D: Transport and Environment*, *17*(5), 380–388. https://doi.org/10.1016/j.trd.2012.03.004

Yu, B., Wang, S., & Gu, X. (2018). Estimation and uncertainty analysis of energy consumption and CO2 emission of asphalt pavement maintenance. *Journal of Cleaner Production*, *189*, 326–333. https://doi.org/10.1016/j.jclepro.2018.04.068

Zalama, E., Gómez-García-Bermejo, J., Medina, R., & Llamas, J. (2014). Road crack detection using visual features extracted by gabor filters. *Computer-Aided Civil and Infrastructure Engineering*, *29*(5), 342–358. https://doi.org/10.1111/mice.12042

Zhang, A., Wang, K. C. P., Li, B., Yang, E., Dai, X., Peng, Y., Fei, Y., Liu, Y., Li, J. Q., & Chen, C. (2017). Automated pixel-level pavement crack detection on 3D asphalt surfaces using a deep-learning network. *Computer-Aided Civil and Infrastructure Engineering*, *32*(10), 805–819. https://doi.org/10.1111/mice.12297

Zhang, A., Wang, K. C. P., Fei, Y., Liu, Y., Tao, S., Chen, C., Li, J. Q., & Li, B. (2018a). Deep learning–based fully automated pavement crack detection on 3D asphalt surfaces with an improved crackNet. *Journal of Computing in Civil Engineering*, *32*(5), 04018041. https://doi.org/10.1061/(asce)cp.1943-5487.0000775

Zhang, D., Zou, Q., Lin, H., Xu, X., He, L., Gui, R., & Li, Q. (2018b). Automatic pavement defect detection using 3D laser profiling technology. *Automation in Construction*, *96*, 350–365. https://doi.org/10.1016/j.autcon.2018.09.019

Zhang, H., Jin, R., Li, H., & Skibniewski, M. J. (2018c). Pavement maintenance–focused decision analysis on concession periods of PPP highway projects. *Journal of Management in Engineering*, *34*(1), 04017047. https://doi.org/10.1061/(asce)me.1943-5479.0000568

Zhang, A., Wang, K. C. P., Fei, Y., Liu, Y., Chen, C., Yang, G., Li, J. Q., Yang, E., & Qiu, S. (2019). Automated pixel-level pavement crack detection on 3D asphalt surfaces with a recurrent neural network. *Computer-Aided Civil and Infrastructure Engineering*, *34*(3), 213–229. https://doi.org/10.1111/mice.12409

Zhong, B., Wu, H., Ding, L., Love, P. E. D., Li, H., Luo, H., & Jiao, L. (2019). Mapping computer vision research in construction: Developments, knowledge gaps and implications for research. *Automation in Construction*, *107*, 102919. https://doi.org/10.1016/j.autcon.2019.102919