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Research Article

Identification and prioritization of key health hazards to workers in roadway construction

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Abstract

Although various rating systems have been developed to promote sustainable development in roadway construction, sustainability evaluation from the perspective of safeguarding workers' health is currently lacking. Three approaches were used in the study to identify and prioritize key health hazards to workers in roadway construction, including bibliometric analysis, questionnaire survey and analytic hierarchy process (AHP). Bibliometric analysis indicates that submicron particles and polycyclic aromatic compounds are the primary concerns of researchers, and ergonomics also attracts some attention. A questionnaire survey was conducted among construction workers in China. The results suggest that the most frequently encountered occupational disorders by roadway construction workers are musculoskeletal disorders, heat stroke, respiratory health issues and hearing loss, and the most commonly encountered hazards are noise, dust, asphalt fumes, heat stress and some adverse working conditions. Perceptions on associations between the health hazards and disorders were obtained. Although there are some discrepancies between the AHP scores provided by two groups of professionals in China, the commonly agreed top occupational hazards include dust, asphalt fumes, noise, high-/low-temperature stresses and chronic injuries. The findings may be incorporated into rating systems for roadway construction to encourage the industry to adopt better practices for the well-being of workers.

Keywords: sustainable construction, occupational health, roadway workers, hazards and exposures, analytic hierarchy process

1. Introduction

Various rating systems have been developed in the construction industry to assess how built facilities in their life cycles are aligned with sustainability principles. Notable examples are rating systems for green buildings, such as the Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM®) [1, 2]. In the systems, comprehensive scoring schemes are developed to encourage the adoption of environmentally friendly and socially responsible building practices. Similar rating systems have been developed for roadway construction projects. Examples include Green Leadership in Transportation Environmental Sustainability, Greenroads®, Illinois-Livable and Sustainable Transportation Rating System and Guide (I-LASTTM) and the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) [3–6]. The rating systems serve as important tools for guiding, assessing and promoting sustainability in the construction industry.

It is recognized, however, that health and safety as an important element in the social dimension of sustainability are often neglected. A White Paper by the US National Institute for Occupational Safety and Health (NIOSH) concluded that sustainable construction practices are mainly involved in improving energy efficiency and reducing construction wastes [7]. Even if the above-mentioned rating systems contain some health elements, the objective of such elements is mainly focused on the health of facility users instead of occupational health during the construction process. Therefore, NIOSH believes that it is necessary to incorporate occupational health in the evaluation tools. This suggestion has prompted the United States Green Building Council to add a pilot credit entitled 'Prevention through Design' to incorporate health and safety considerations in LEED. Failure to include health and safety components in project sustainability evaluation does not well reflect the Sustainable Development Goals (SDGs) developed by the United Nations either [8]. SDGs provide a common ground on the interpretation of sustainable development among international communities [9]. According to Goal 3 of the SDGs, the number of deaths and illness resulting from hazardous chemicals and pollution should be substantially reduced by 2030. The construction sector employs a large number of workers and creates non-negligible occupational hazards; hence improvements on health and safety in construction would help achieve the SDGs.

Roadways are an important component of modern transport systems. Every year, a large amount of financial resource is invested in the new construction, rehabilitation and maintenance of roadways. From 2010 to 2020, investment in road construction in China increased from around 164 billion U.S dollars per year to 347 billion U.S. dollars per year [10, 11]. By the end of 2020, the total length of the roadway network in China had reached about 5,200,000 km, including 161,000 km of highways [10, 12]. In the USA, around 100 billion U.S. dollars were spent by the public sector on roadway construction in 2019 [13]. The roadway construction industry also employs a large number of workers. Statistics on the exact number of workers involved in roadway construction are hard to find in China. In the US, nearly 150,000 workers were employed in 2020 for roadway maintenance work alone [14], while the number of workers for new construction and rehabili-

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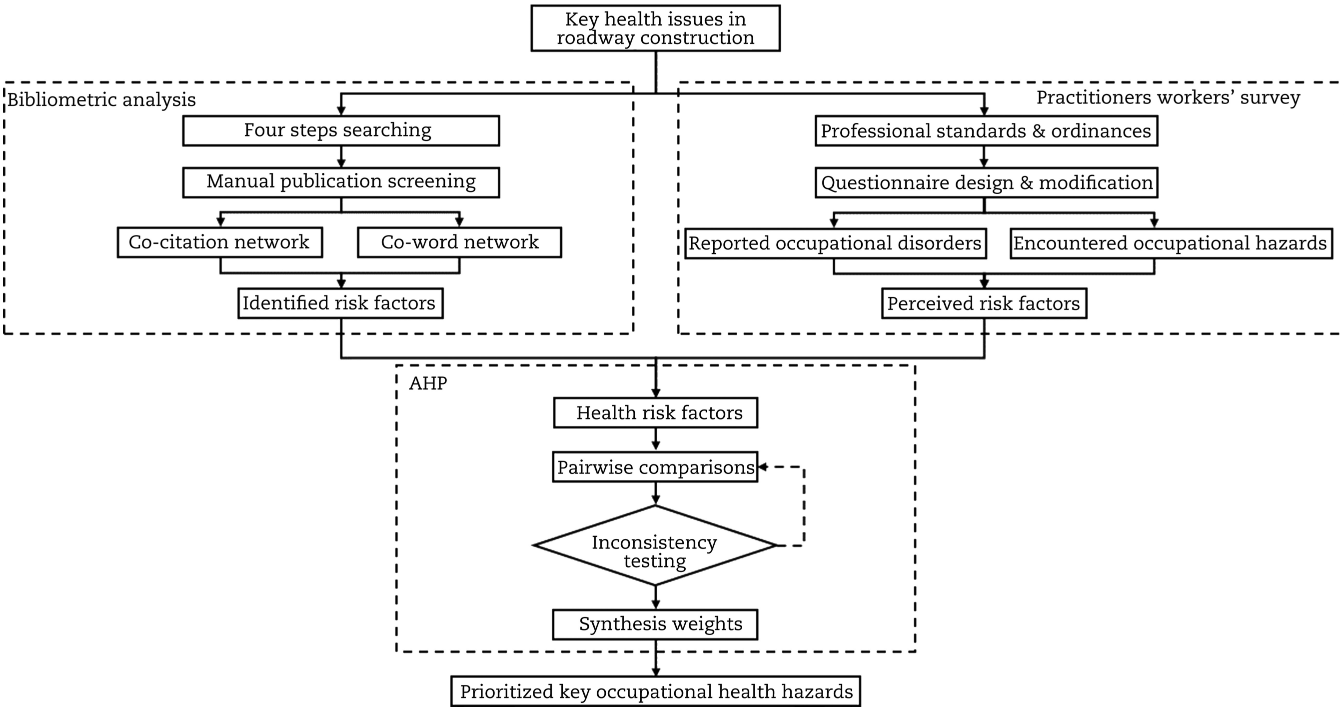

Fig. 1. The methodological framework.

tation is hard to estimate because they may also simultaneously participate in other types of heavy construction works. Roadway construction has unique characteristics that lead to some special health concerns. For instance, the majority of paved roads need to be constructed at high temperatures, which leads to the high emission of organic compounds and aerosols from asphalt paving materials. Construction workers are inevitably exposed to such emissions. Their health, however, is currently not included in project life-cycle assessment tools for roadway construction. It is also noted that roadway construction technologies are quite similar around the world, including construction materials, equipment and procedures. Therefore, potential health hazards faced by workers in one geographical context are likely to be faced by workers in other places, except for those related to climate and altitude.

This study aims to identify and prioritize key occupational health hazards during roadway construction so that such hazards can be considered in assessing the overall sustainability of roadway construction projects. In addition, it is anticipated that the research will help the industry better recognize those hazards and develop more socially responsible production practices to protect the well-being of roadway construction workers. The main research components, including a questionnaire survey and evaluation of health factors by professionals, took place in China, while literature review involved academic studies conducted worldwide on the relevant topics.

2. Methods

Three approaches were used in the study. First, bibliometric analysis was performed to assist a systematic review on existing studies. The purpose of bibliometric analysis is to identify existing relevant research topics and findings from academics. Second, questionnaire surveys were conducted among roadway construction practitioners in China. The purpose of questionnaire survey is to obtain first-hand experiences and perceptions from the practitioners. Third, the relative importance of possible harmful factors, which were obtained from the previous two research components, was evaluated by construction managers and health professionals in China based on the analytic hierarchy process (AHP) method. The purpose is to consolidate the research findings and prioritize the identified hazards. The research methodology is shown in Fig. 1 and explained as follows.

2.1 Bibliometric analysis

Bibliometric analysis was conducted to analyse existing research on occupational health hazards related to roadway construction. Different to a haphazard literature review, bibliometric analysis is a systematic and rigorous approach to mapping a specific knowledge domain from existing literature. A key component of bibliometric analysis is citation analysis, based on which one can obtain information such as time series and geographical distributions of published documents on a specific topic, interrelationships among the documents, and the popularity and impacts of the publications [15, 16]. Particular questions concerned in this study include the following. (1) What harmful factors in roadway construction are commonly concerned and researched? (2) Can the existing research be grouped into major topical themes based on their similarities and connections?

Although there are a variety of publications, the focus was placed on published articles indexed by Web of Science (WOS) and Scopus® because citation analysis can be conveniently performed on such documents. When retrieving data from existing literature, an important issue is to properly handle precision (retrieval relevance) and recall (retrieval completeness) [17]. A four-step backward search strategy, proposed for improving both precision and recall simultaneously [18, 19], was adopted in this study. The de-

Table 1. The list of occupational hazards included in the survey

Possible occupational hazard	Abbreviation
Asphalt fumes	AF
Acute injuries	AI
Cumulative injuries	CI
Dust	Dust
High-temperature stress	HS
Work in a humid environment	HU
Low-temperature stress	LS
Nightshift construction	NC
Noise	Noise
Rainy-day construction	RC
Work at high altitude	WA
Work-related fatigue	WRF
Work in underground tunnel/culvert	WTC

Table 2. The list of occupational disorders in the survey

Possible occupational disorder	Abbreviation
Acne	Ac
Altitude sickness	AS
Asthma	Asth
Cataract	Cat
Chemical eye burns	CEB
Chemical skin burns	CSB
Chest congestion	CC
Dry cough	DC
Frostbite	Frost
Hearing loss	HL
Heat stroke	HSk
Melanosis	Mel
Musculoskeletal disorders	MSDs
Ophthalmia	Oph
Other respiratory diseases	ORD
Pneumoconiosis	Pneu
Silicosis	Sil
Skin inflammation	SI
Skin ulcers	SU
Vitiligo	Vit

tailed search process is presented in the Appendix. At the end of the search process, a total of 179 articles were retrieved.

Not all papers obtained from the search are closely related to this study. Therefore, the papers were further manually screened, based on the principle that the main content of the paper should be focused on occupational health hazards in roadway construction. Those dealing with work-zone safety, legislation issues, etc. were not considered. As a result of further refinement, a total of 66 papers were finally selected for detailed analysis.

The software Citespace was adopted for analysing the data and visualizing the results [20], through which the associations among relevant publication indexing terms were identified [21]. The software can help plot nodes and their connections.

The nodes represent individual articles' descriptors that can be automatically classified; the size of nodes represents their relative importance, and the links among nodes indicate their relationships. Moreover, based on the associations of the nodes, key research concepts can be clustered in groups. The groups may intuitively indicate a 'distinct specialty' or a 'thematic concentration' [22]. Such information is useful for understanding the literature landscape concerning a particular topic.

One of the major methods in bibliometric analysis is to constitute an intellectual base by co-citation network [23, 24]. Co-citation is a process in which two publications are cited together in a new document [25, 26]. Through co-citation, published documents are linked together, similar to the co-occurrence of words [27, 28]. The analysis of co-citations enables researchers to identify connections between publications, cluster the research areas and identify 'research foci' [29–31]. By calculating the relationships and network attributes, Citespace can group and visualize the co-citation network. Moreover, Citespace can automatically create a label for each cluster, based on the phrases extracted from the titles, keywords and abstracts of the cited papers [20]. This label reveals the nature of the closely related research areas, potentially serving as keywords for the concerned health issues.

While the co-citation network maps research density areas based on jointly cited publications, the co-word network is another commonly used method in bibliometric analysis which deals with 'the patterns of word usage' to map the semantic structure of a field and facilitate the cognitive understating of such an area [31–35]. Co-word network reveals the co-occurrence of key terms (words) across different publications. Co-word analysis can identify the network of key concepts by extracting those frequently used terms and elucidate their interactions [21, 35–37].

2.2 Questionnaire Survey

To obtain direct responses from practitioners, a questionnaire survey was conducted among roadway construction workers. Besides collecting basic information from the respondents, the survey questionnaire was designed to obtain two types of information: (1) what occupational hazards are of most concern to the workers and (2) to what extent they believe those factors affect their health, or occupational disorders. A list of occupational hazards was developed for the respondents to consider (Table 1). Some items on the list were obtained from the bibliometric analysis and the others were taken from the occupational health hazard classification developed by a government agency [38]. In view of the special characteristics of roadway construction, five work scenarios that may affect workers' health were also included after consulting with industry professionals, including nightshift construction, rainy-day construction, work in underground tunnels and culverts, work in humid environments and work at high altitude. In addition, work-related fatigue, a frequently discussed physiological state in literature, was also added [39–41].

A list of occupational disorders were also developed and included in the survey. The purpose of the disorder list is to: (1) understand the general health state of the survey respondent and (2) facilitate the respondents to identify possible perceived relationships between the occupational hazards and disorders. The preliminary list of disorders was selected from the Chinese Classification and Catalog of Occupational Disease [42]. The preliminary list was sent to five experts for refinement: two consultants from an occupational health and safety agency, two medical doctors and an academic staff member specializing in public health. After the refinement, a total of 20 disorders were finally included in the questionnaire, as shown in Table 2.

It is noted that the relationships identified by the workers are 'perceived' risks, not actual risks. Because the occupational disorders may be affected by many confounding factors, extensive cohort studies would be requested to identify even one causal relationship between the disorder and hazard. For instance, in asphalt fume studies, it is not uncommon that researchers may take 10 or more years to trace the specific construction workers' groups [43, 44]. The large number of combinations of disorders and hazards

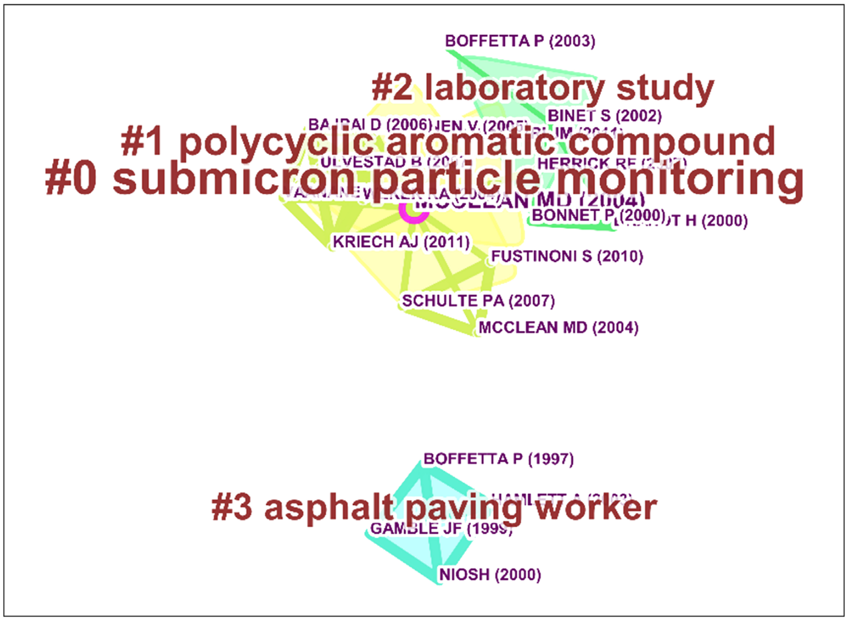

Fig. 2. Co-citation network generated by Citespace.

would require a significant amount of time and resources for this kind of investigation. This study is focused on workers' perceptions on health hazards. Perception-based studies are often used in health research. For instance, Meni *et al.* [45] examined the correlation between heart disease and self-perceived causes; White *et al.* [46] investigated the self-reported causes among people who suffer chronic fatigue syndrome.

2.3. Assessment from construction managers and health professionals

While the perceived health hazards from workers were obtained from the questionnaire survey, further assessment from managers and health professionals were collected based on a more detailed analysis tool—the AHP analysis, a widely used method for formulating and aiding decision-making [47–49]. The AHP analysis can generate numerical weights or indicators through pair-wise comparisons based on experts' judgements [50, 51]. Systematic pair-wise comparison and consistency check have the advantage of obtaining more logic and consistent judgements. With the assistance of this scoring system, the occupational health risks could be assessed and quantified. For instances, Yeo *et al.* [52] assess health hazards in the production of printed paper packages. Arslan [53] identifies and prioritizes the health and safety hazards during chemical cargo operations.

3. Results and discussion

3.1 Results from bibliometric analysis

3.1.1 Co-citation network

The generated co-citation network is presented in Fig. 2. Several findings can be made from the co-citation network. First, the largest cluster is 'submicron particle monitoring', followed by 'polycyclic aromatic compound' (PAC). This indicates that the predominant health issues concerned by researchers are exposure to particulate matters, especially organic particulate matters in asphalt fumes. Second, the links between the clusters suggest that existing studies on particulate matters are closely related to PAC, and the studies on PAC are laboratory-based. Conversely, studies on 'asphalt paving worker' is more independent. The findings suggest that studies on particulate matters containing PAC are conducted more frequently in the laboratories than in the field. Third, a further analysis of the cluster 'asphalt paving worker' suggests that the cited publications focus on possible illness caused by hazards, including possibly increased lung cancer mortality risk [54], lung function and symptoms associated with asphalt fumes and working conditions [55].

3.1.2. Co-word network

Standardization was manually conducted before co-word analysis because Citespace cannot automatically handle the same concept with different acronyms or abbreviations [56]. For example, the acronym PAHs is often used exchangeable with other terms, including polycyclic aromatic hydrocarbons, polycyclic aromatic compounds and polycyclic aromatic hydrocarbons – PAHs. Roadway construction workers are sometimes also expressed as roadway asphalt paving crew, asphalt paving workers, construction workers, construction worker, hot-mix asphalt paving operators, paving workers, etc.

The co-word network is presented in Fig. 3. Three agglomerations can be easily detected from the network: (1) exposure of roadway construction workers to asphalt fumes, (2) exposure to silica and (3) ergonomics. As compared with the co-citation network, the co-word network reveals two additional health concerns by researchers: silica dust and ergonomics. Because the size of the clusters indicates the frequency of the keywords and the size of the nodes indicates the strength of their associations, it is obvious that asphalt fumes and silica dust attract more attention than ergonomics. Within each cluster, the co-word network also shows how the key terms are connected. For instance, the largest cluster demonstrates that PAHs is the main concern for inhalation exposure of hot-mix asphalt construction workers.

In summary, the co-citation network analysis generates four major clusters: (1) submicron particle monitoring, (2) polycyclic aromatic compound, (3) laboratory study and (4) asphalt paving workers. The result suggests that submicron particles and PACs (through inhalation of asphalt fumes and/or dermal exposure to

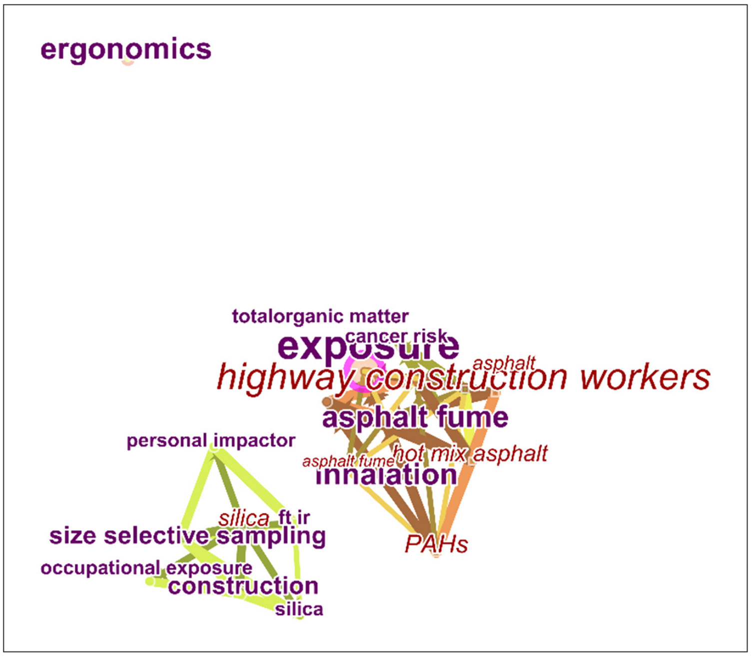

Fig. 3. Co-word network generated by Citespace.

asphalt materials) are the primary concerns, which are currently mainly assessed through laboratory studies. The main susceptible group is asphalt paving workers. The co-word network analysis produces three agglomerations: (1) inhalation exposure to asphalt fumes and dermal exposure to asphalt, (2) exposure to silica-containing dust and (3) ergonomics.

3.2 Perception of health hazards by roadway construction workers

The questionnaire survey was conducted among on-site workers from 13 roadway construction projects in Mainland China in 2017. A total of 166 valid responses were obtained. The mean age of the respondents is 33 years with a standard deviation of 7 years. About 80% of on-site workers are male. The mean weight of male workers is 64.9 kg with a standard deviation of 9.5 kg. For female workers, the mean weight is 54.1 kg with a standard deviation of 9.4 kg. As compared with the average weight of Chinese residents [57]—male 66.2 kg and female 57.3 kg—the average weights of the respondents are less. The smoking and drinking habits of the workers were also surveyed. Three choices were provided to the subjects: an active smoker, never being a smoker and having quit smoking. Drinking behaviours were questioned in the same manner. The results show that nearly 30% ($N = 46/166$) of workers are active smokers, and about 27% ($N = 44/166$) are active drinkers. Approximately 17% of the workers quit smoking and about 10% quit drinking. About 56% of the respondents never smoked and about 60% never drank alcohol. The drinking and smoking behaviours affect the health conditions of the workers, making it difficult to separate actual health 253 problems due to occupational hazards [58–60].

Fig. 4 displays the frequency plot of occupational disorders self-reported by the respondents. Approximately 55% of the workers reported that they suffered from the MSDs and about 30% had experience of heat stroke. These two frequently reported disorders are followed by dry cough, asthma and chest congestion, all of which belong to respiratory health issues. Other disorders such as hearing loss are reported less frequently. Five types of disorders, including altitude sickness, cataract, ophthalmia, skin inflammation and skin ulcers, were not reported by any worker.

The encountered occupational hazards by the roadway construction workers are summarized and presented in Fig. 5. The most frequently encountered hazard is noise (some 50%), followed by dust (about 36%) and asphalt fumes (about 20%). Heat stress (about 18%) is also frequently experienced by the workers, likely to be associated with hot-mix asphalt pavement construction. About 15% of the workers had nightshift construction and up to approximately 13% experienced working in a rainy environment. The least experienced occupational hazards include cumulative injuries, working at plateaus and acute injuries.

The overall associations between occupational disorders and health hazards, as perceived by the workers, are summarized and presented in Fig. 6. The figure shows the strength of associations between occupational disorders and health hazards as perceived by the respondents. Some of the associations are straightforward because the workers only pointed out one contributory source. For instance, frostbite is caused by low-temperature stress, heat stroke is caused by high-temperature stress, altitude sickness is caused by working at high altitude and hearing loss is caused by noise. Some disorders are believed to be associated with multiple hazards. For instance, occupation-related dry cough is believed to be related to asphalt fumes, dust and to a lesser extent a few other factors.

Fig. 6 also reveals some information on the degree of concern about the disorders or hazards, manifested in the length of the segments in the circle. MSDs are not only related to several hazards, but the strengths of the associations are also strong. This implies that the workers are concerned about MSDs as well as the contributory factors. Conversely, asphalt fumes and dust are strongly associated with a variety of disorders, indicating that these two hazards are of more concern to the workers.

To more clearly show the perceived associations, the occupational hazards are also divided into three groups (hazardous exposure, physiological states and work scenarios) and presented

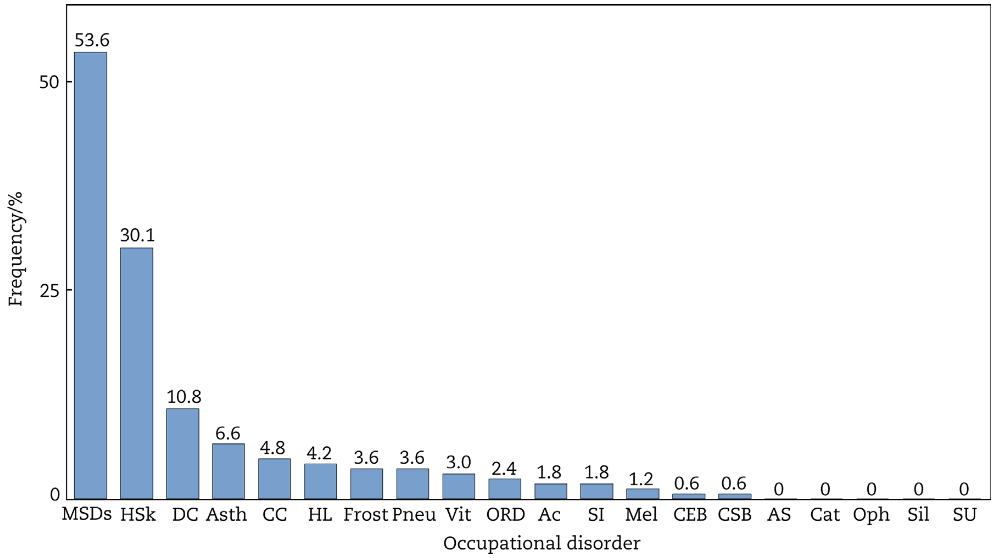

Fig. 4. Frequency of reported occupational disorders by workers.

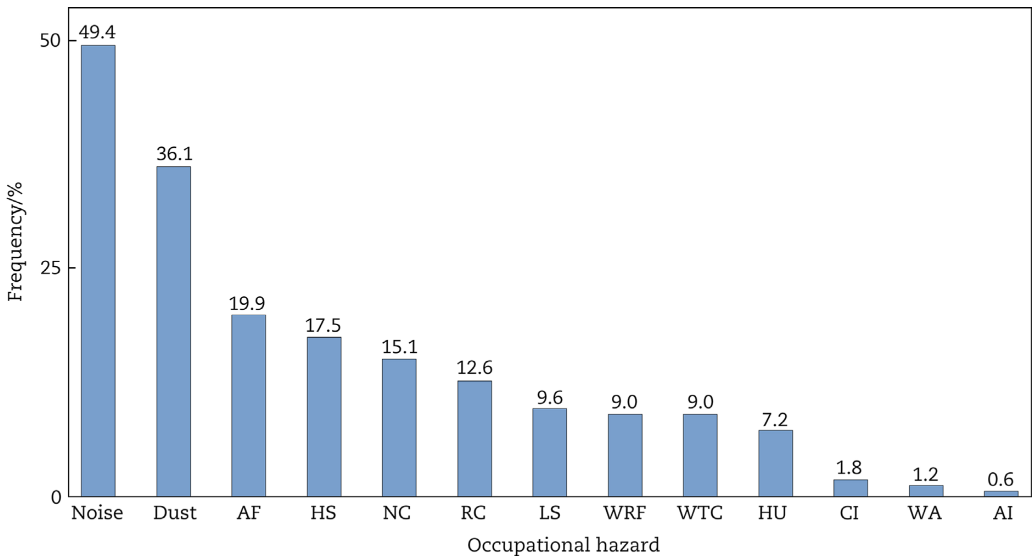

Fig. 5. Frequency of encountered occupational hazards by workers.

separately in Figs. 7-9. The color and size of the nodes indicate the strengths of associations perceived by the workers. Fig. 7 indicates that asphalt fumes and dust equally contribute to a variety of respiratory disorders. Heat stress is believed to cause not only heat stroke but also MSDs, indicating that hot environments affect workers' feeling about the overall fitness of their bodies.

Fig. 8 demonstrates the perceived relationships between three physiological states (acute injuries, cumulative injuries and work-related fatigue) and a variety of disorders. All three hazards are closely related to MSDs. To a lesser extent, work-related fatigue is also related to several respiratory disorders. The workers may feel that such disorders may be aggravated by work-related fatigue, or such disorders further cause work-related fatigue. It is noted that work-related fatigue has received wide attention in several other industries. For instance, the aviation industry takes such a problem quite seriously [61, 62] and has developed a management model for evaluating and managing work-related fatigue [63, 64].

Fig. 9 shows the relationships between the perceived occupational disorders and special work scenarios, including work in a humidity environment, nightshift construction, rainy-day construction, work at high altitude and work in underground tunnels/culverts. The responses suggest that these work scenarios are associated with MSDs. The workers believe that the stressful and unpleasant environment may at least partially contribute to MSDs. In addition, working at high altitude and in underground environments is also believed to contribute to a variety of respiratory disorders. Existing studies also suggest adverse working environments such as humidity undermine workers' performance and health condition [65–68].

3.3 Prioritization of hazards by professionals

The hierarchical framework of the AHP is shown in Fig. 10, which includes the overall goal, criteria and sub-criteria. The overall goal is to prioritize key health issues in roadway construction,

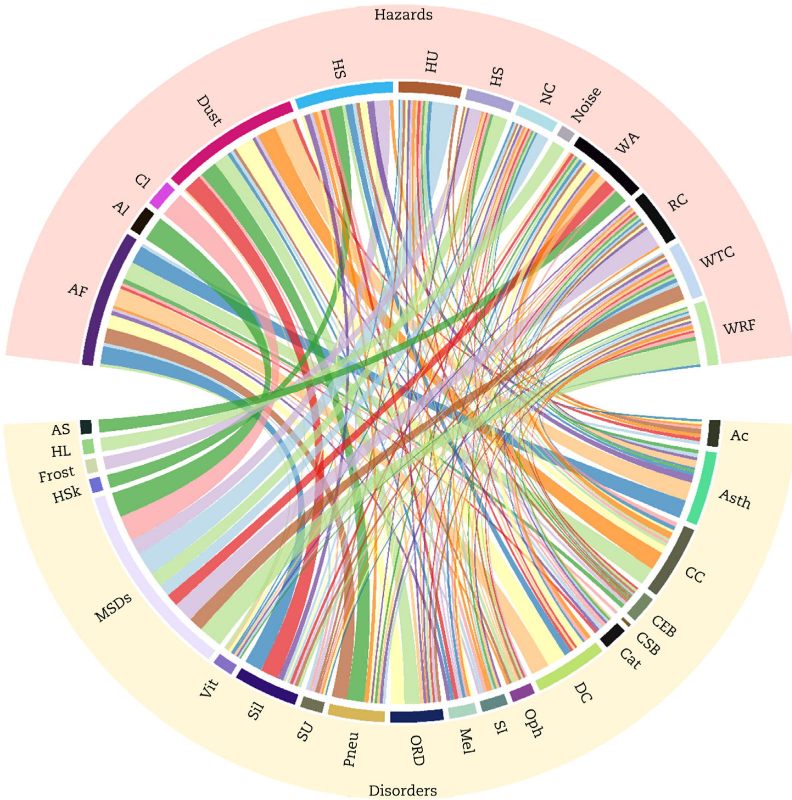

Fig. 6. Holistic perception of on-site roadway construction workers.

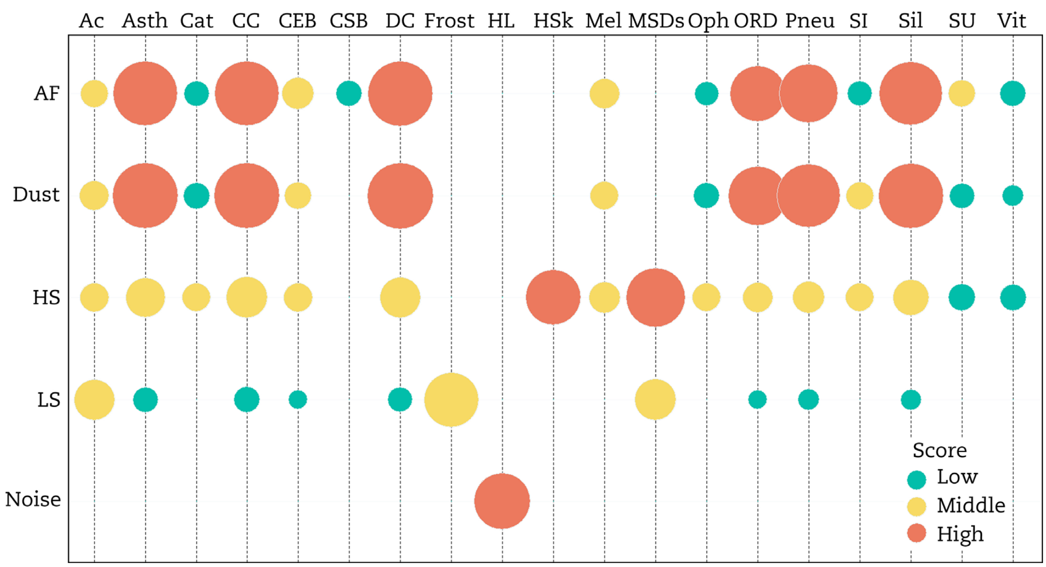

Fig. 7. Perception of occupational disorders due to hazardous exposures.

which are classified into three groups (criteria): construction-related environmental factors, hazardous exposures and physiological states. Under the criteria are the specific hazards (sub-criteria) for which the respondents were asked to make pair-wise comparisons and numerically assess their relative importance with the consideration of both occurrence frequency and consequence.

Eight sub-criteria are included in the AHP framework. Both 'hazardous exposure' and 'physiological states' contain three sub-criteria, and 'special work scenarios' contain two sub-criteria.

Obviously, asphalt fumes (AF) and dust should be included under 'hazardous exposure', not only because both of these hazards can be directly observed on the co-words network, but also because they are frequently mentioned in the results of the on-site

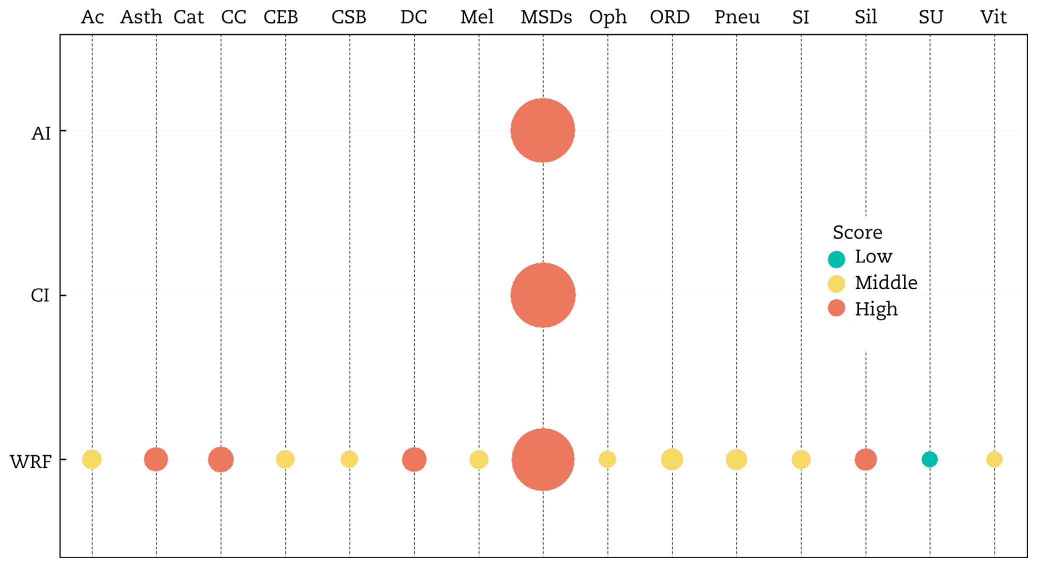

Fig. 8. Perception of occupational disorders due to physiological states.

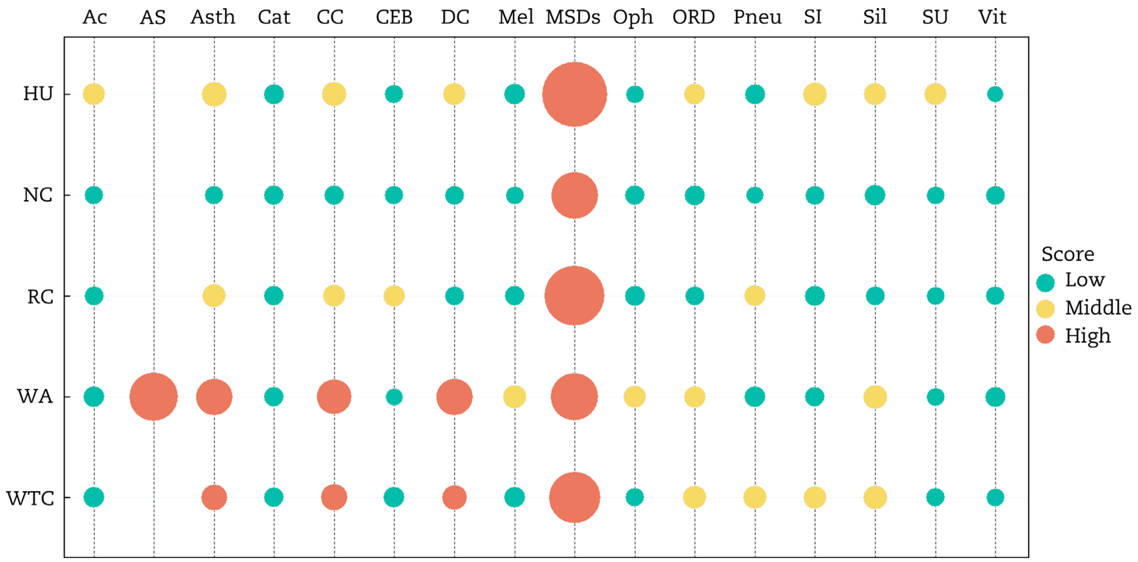

Fig. 9. Perception of the associations between occupational disorders and special work scenarios.

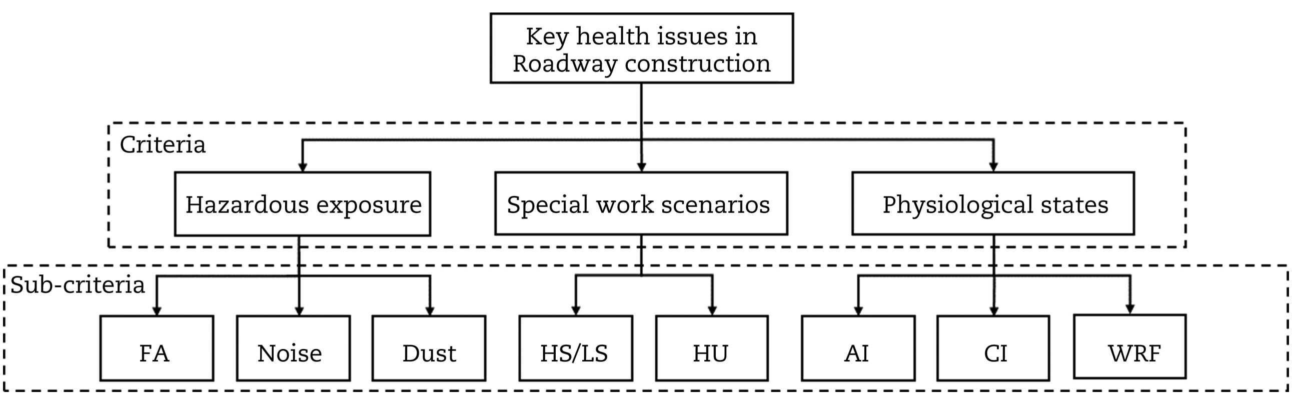

Fig. 10. The framework of AHP for prioritizing health risk factors.

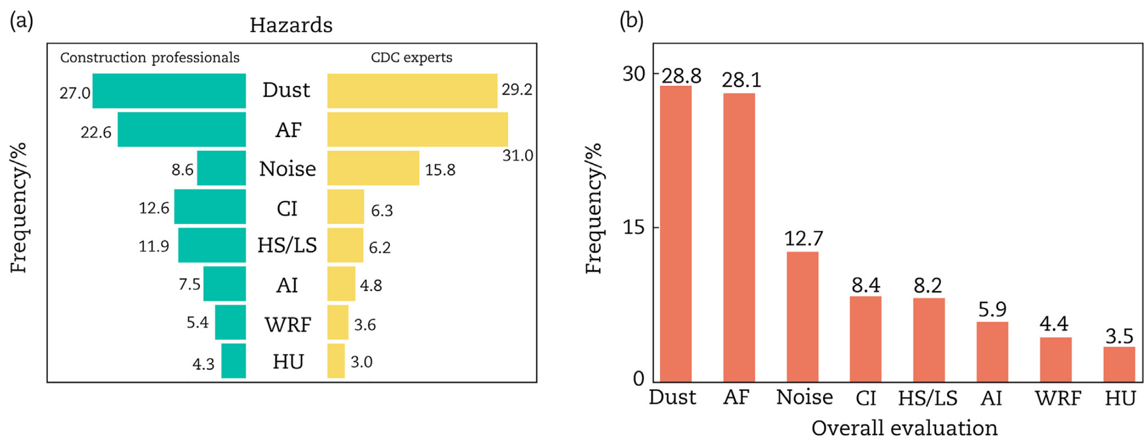

Fig. 11. Prioritization and ranking of the health hazards by (a) groups of construction professional and CDC experts; (b) their overall evaluation.

workers' survey. Additionally, the results of surveys also reveal another sub-criterion of hazardous exposure—noise. It is known that noise-induced hearing loss is widely considered as a health risk globally [69–71]. Researchers from the World Health Organization and other institutions conclude that hearing loss is primarily attributed to occupational exposure to noise [66–68, 72]. Therefore, this hazard is also included in the group of hazardous exposure.

The sub-criteria under 'special working scenarios' are derived from the survey results. Based on the perceptions and experiences of on-site workers, work in a humid environment (HU), high-temperature stress (HS), low-temperature stress (LS) and work at high altitude are the major occupational hazards that potentially undermine their physical health. There are some special guidelines for working at high altitude and it is not commonly encountered; therefore, this hazard is not selected as a sub-criterion. Due to their similar nature, high-temperature stress and low-temperature stress are grouped into one sub-criterion.

'Physiological states' contains acute injuries (AI), cumulative injuries (CI) and work-related fatigue (WRF). Both AI and CI are obtained from the co-words network under ergonomics [73, 74] and they are also frequently mentioned in the survey. WRF is selected because it is selected by the surveyed workers and is also considered as one of the key occupational hazards in other construction jobs, including work from height and the oil and gas construction industry [39, 75].

Professional construction managers and public health professionals were asked to prioritize the health hazards using the AHP technique. The group consists of 10 construction managers and 15 experts mainly from a Center for Disease Control and Prevention (CDC) in Mainland China. Each member was asked to conduct pair-wise comparisons on the eight hazards and provide a numerical rating to the 'more concerned' factor for each pair based on the standard AHP rating scale. The degree of concern should reflect both the occurrence likelihood and health implications of the hazards. Computation of the weightings was performed by the authors, in addition to checking for consistency ratio. Responses with a consistency ratio larger than the recommended thresholds were not included in the final consolidated results [76]. Fianlly, 6 of 10 respondents in the construction manager group and 9 of 15 respondents in the CDC expert group achieved the required consistency. The valid rank scores were averaged to represent the perceptions of the construction managers and health professionals, as shown in Fig. 11.

Collectively, construction managers assigned the highest weight of 27% to dust, followed by asphalt fumes (22.6%) and cumulative injuries (12.6%). Construction managers apparently believe that reductions in dust and asphalt fumes are the most critical for enhancing workers' occupational health. The top three hazards are followed by heat/low-temperature stress (11.9%) and noise (8.6%). Acute injuries, work-related fatigue and work in a humid environment recorded weighted scores of 7.5%, 5.4%, and 4.3%, respectively. It is noteworthy that high-/low-temperature stresses have a weighted score of 11.9%, indicating that this issue arouses much attention from construction managers. However, publications on this issue are relatively rare.

Experts in CDC also perceived that dust (29.2%) and asphalt fumes (31%) are the occupational hazards of most concern for roadway construction workers, although asphalt fumes are assigned a slightly higher priority. They also assigned a relatively higher weight to noise (15.8%). Despite the difference in order, the top five occupational hazards rated by the construction managers and health professionals are the same. They include dust, asphalt fumes, noise, high-/low-temperature stresses and chronic injuries.

The average scores from the two groups are also presented in Fig. 11. It is apparent that dust and asphalt fumes are the most concerning occupational hazards, immediately followed by noise. chronic injuries, high-/low-temperature stresses, acute injuries, work-related fatigue, and humidity have weights of 8.4%, 8.2%, 5.9%, 4.4% and 3.5%, respectively.

4 Summary and conclusions

Roadway construction is an important sector of the construction industry and employs a large number of workers. The construction industry has developed and adopted various rating systems to advocate sustainable construction practices. However, the health and safety of construction workers—an important element in sustainability—are often neglected. This research used three methods to identify and prioritize key occupational health hazards during roadway construction. First, bibliometric analysis was performed to symmetrically analyse existing relevant research topics and findings from academics. Second, questionnaire surveys were conducted among roadway construction workers to obtain their first-hand experiences and perceptions. Third, the relative importance of hazardous factors was evaluated by construction managers and health professionals based on the AHP approach.

Bibliometric analysis indicates that submicron particles (dust) and PACs (through inhalation of asphalt fumes and/or dermal exposure to asphalt materials) are the primary concerns, and the main group susceptible is asphalt paving workers. In addition, ergonomics also attracts attention from researchers.

Survey results suggest that the most frequently encountered occupational disorders by roadway construction workers are MSDs, heat stroke, respiratory health issues and hearing loss. The most commonly encountered health hazards are noise, dust, asphalt fumes, hot-temperature stress and some adverse working conditions. Perceptions on possible associations between the health hazards and disorders were also obtained, providing more comprehensive information on the health factors of most concern to the workers.

Although there are some discrepancies between the AHP weight scores provided by construction managers and health professionals, they commonly agree that dust, asphalt fumes, noise, high-/low-temperature stresses and chronic injuries are the top occupational hazards encountered by workers.

Results from the three research methods all lead to some commonly concerning health issues in roadway construction, including inhalable organic/inorganic particles and MSDs that are likely related to ergonomics. On the other hand, there are some different emphases for different groups. In particular, construction workers are more concerned with noise and temperature-related stresses that are not widely discussed in literature. Such research gaps call for attention from academia. In addition, the type and priority of health hazards identified in this study may be incorporated in rating systems for assessing the overall sustainability of roadway construction projects in the future. It is also anticipated that the research will help the industry recognize those health hazards and develop better practices to address those specific concerns.

Supplementary data

Supplementary data is available at *Transportation Safety and Environment* online.

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Conflict of interest statement

The authors declare that there are no potential conflicts of interest in the publication of this research output.

References

1. BRE (Building Research Establishment) Global, *BREEAM International New Construction 2016 Technical manual SD5073 2.0*. 2016; BRE Global Ltd, Watford.
2. U.S. GBC (Green Building Council), LEED v4 for Building Design and Construction. 2014.
3. U.S. NYSDOT, *GreenLITES Project Design Certification Program (version 2.1.0)*. 2010, New York State Department of Transportation.
4. U.S. IDOT (Illinois Department of Transportation),IRTBA, and ACEC-IL, *Illinois-Livable and Sustainable Transportation Rating System and Guide*. Illinois Department of Transportation, 2012.
5. Anderson J, Weiland C, Muench S, *Greenroads Manual v1. 5*. 2011, University of Washington: Seattle, WA.
6. U.S. FHWA (Federal Highway Administration), INVEST Economic Social Environmental Sustainable Highways Self-Evaluation Tool, in *INVEST Version 1.3*. 2018, Federal Highway Administration: Washington, DC.
7. NIOSH (National Institute for Occupational Safety and Health), NIOSH Perspectives on Sustainable Buildings: Green … and Safein *NIOSH Perspectives on Sustainable Buildings* 2010, DHHS (NIOSH): Cincinnati, OH. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.
8. UNGA (United Nations General Assembly), Transforming our world: the 2030 Agenda for Sustainable Development. 2015, UN.
9. UNDP (United Nations Development Programme). *The SDGs in action*. 2021 [cited 2021 30 December]; Available from: https://www.undp.org/sustainable-development-goals?c_src=CENTRAL&c_src2=GSR.
10. China MOT (Ministry of Transport). '2020 nian jiaotong yunshu hangye fazhan tongji gongbao [Statistical Bulletin on the Development of the Transportation Industry],' 2021 [cited 2021 13 May]; available from: http://www.gov.cn/xinwen/2021-05/19/content_5608523.htm.
11. China MOT (Ministry of Transport), '2010 nian gonglu shuilu jiaotong yunshu hangye fazhan tongji gongbao [Statistical bulletin on developments in the roadway and waterway transportation industries.],' 2011 [cited 2021 16 December]; available from: https://www.mot.gov.cn/fenxigongbao/hangyegongbao/201510/t20151013_1894757.html.
12. Li Z G, Wu M Q, Chen B R, Is road infrastructure investment in China excessive? Evidence from productivity of firms.. *Region Sci Urban Econ* 2017;**65**:116–126.
13. U.S. Census Bureau. Construction Spending. 2021[cited 2021 25 Dec]; available from: https://www.census.gov/construction/c30/historical_data.html.
14. U.S. Bureau of Labor Statistics (BLS). 47-4051 Highway Maintenance Workers Occupational Employment and Wages, May 2020 2021 March 31, 2021 [cited 2021 7 September]; available from: https://www.bls.gov/oes/current/oes474051.htm.
15. Blaise C, Bibliometrics and beyond: some thoughts on web-based citation analysis. *J Inform Sci* 2001; **27**: 1–7.
16. Börner K, Chen C, Boyack Kevin W, Visualizing knowledge domains. *Ann Rev Inform Sci Technol* 2003; **37**: 179–255.
17. Buckland M, Gey F, The relationship between recall and precision. *J Am Soc Inform Sci* 1994; **45**: 12–19.
18. Haunschild R, Bornmann L, Marx W, Climate change research in view of bibliometrics. *PLoS One* 2016; **11**: e0160393.
19. Wang B, et al. An overview of climate change vulnerability: a bibliometric analysis based on Web of Science database. *Natur Haz* 2014; **74**:1649–1666.
20. Chen C, CiteSpaceI I: Detecting and visualizing emerging trends and transient patterns in scientific literature. *J Am Soc Inform Sci Technol* 2006; **57**: 359–377.
21. Coulter N, Monarch I, Konda S, Software engineering as seen through its research literature: A study in co-word analysis. *J Am Soc Inform Sci* 1998; **49**: 1206–1223.
22. Chen C, Dubin R, Kim M C, Orphan drugs and rare diseases: a scientometric review (2000 –2014). *Expert Opin Orphan Drugs* 2014; **2**:709–724.
23. Diodato V P, *Dictionary of bibliometrics*. 1994, New York: Haworth Press.
24. Persson O, The intellectual base and research fronts of JASIS 1986–1990. *J Am Soc Inform Sci* 1994; **45**:31–38.

25. Egghe L, Rousseau R, *Introduction to informetrics: Quantitative methods in library, documentation and information science*. 1990: Elsevier Science Publishers.
26. Small H, Co-citation in the scientific literature: A new measure of the relationship between two documents. *J Am Soc Inform Sci* 1973. **24**:265–269.
27. Osareh F, Bibliometrics, citation analysis and co-citation analysis: A review of literature. 1. *Libri* 1996; **46**:149–158.
28. Small H, Upham P, Citation structure of an emerging research area on the verge of application. *Scientometrics* 2009; **79**:365–375.
29. Braam R R, Moed H F, Vanraan A F J, Mapping of science by combined co-citation and word analysis. II: Dynamical aspects. *Sci Technol Human Val* 1988. **13**(1-2): 98–98.
30. Small H G, A co-citation model of a scientific specialty: A longitudinal study of collagen research. *Social Stud Sci* 1977;**7**: 139–166.
31. Small H, Griffith B C, The structure of scientific literatures I: Identifying and graphing specialties. *Sci Stud* 1974; **4**:17–40.
32. Braam R R, Moed H F, Van Raan A F, Mapping of science by combined co-citation and word analysis I. Structural aspects. *J Am Soc Inform Sci* 1991; **42**:233.
33. Bhattacharya S, Basu P K, Mapping a research area at the micro level using co-word analysis. *Scientometrics* 1998; **43**:359–372.
34. Aria M, Cuccurullo C, bibliometrix: An R-tool for comprehensive science mapping analysis. *J Informetr* 2017; **11**:959–975.
35. Callon M, et al. From translations to problematic networks—An introduction to co-word analysis. *Soc Sci Inform sur les Sci Sociales* 1983; **22**:191–235.
36. Callon M, Courtial J P, Laville F, Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemsitry. *Scientometrics* 1991; **22**:155–205.
37. Jean-Pierre C, John L, A co-word study of artificial intelligence. *Soc Stud Sci* 1989; **19**:301–311.
38. China NHFPC (National Health and Family Planning Commission), 'Guanyu yinfa zhiyebing weihai yinsu fenlei mulu de tongzhi [Notice of the Classification Catalogue of Occupational Disease Hazards]', NHFPC, Editor. 2015, Beijing.
39. Chang F L, et al. Work fatigue and physiological symptoms in different occupations of high-elevation construction workers. *Appl Ergon* 2009; **40**:591–596.
40. Jones M K, et al. Work-related health risks in Europe: Are older workers more vulnerable? *Soc Sci Med* 2013; **88**: 18–29.
41. Canadian Center for Occupational Health and Safety (CCOHS). Fatigue. 2017 16 February 2021 [cited 2021 7 September]; available from: https://www.ccohs.ca/oshanswers/psychosocial/fatigue.html.
42. China NHFPC (National Health and Family Planning Commission), 'Zhonghua renmin gongheguo guojia weisheng he jihuashengyu weiyuanhui gongbao [Gazette of the National Health and Family Planning Commission of People's Republic of China]', NHFPC, Editor. 2013, Beijing.
43. Hansen E S, Cancer mortality in the asphalt industry: A ten year follow up of an occupational cohort. *Br J Indust Med* 1989; **46**: 582.
44. Sjödahl K, et al. Airborne exposures and risk of gastric cancer: A prospective cohort study. *Int J Cancer* 2007; **120**:2013–2018.
45. Meni K, Sydney H C, La V Lawrence, Perception of the etiology of illness: Causal attributions in a heart patient population. *Perceptual Motor Skills* 1978; **47**:475–485.
46. White K, et al. Causal attributions, perceived control, and psychological adjustment: A study of chronic fatigue syndrome 1. *J Appl Soc Psychol* 2006; **36**:75–99.
47. Saaty T L, 1988 *What is the analytic hierarchy process?*in Berlin, Heidelberg. Springer.
48. Saaty T L, How to make a decision: The analytic hierarchy process. *Eur J Oper Res* 1990; **48**:9–26.
49. Vaidya O S, Kumar S, Analytic hierarchy process: An overview of applications. *Eur J Operat Res* 2006; **169**:1–29.
50. Forman E H, Gass S I, The analytic hierarchy process—An exposition. *Operat Res* 2001; **49**:469–486.
51. Saaty T L, Some Mathematical Topics in the Analytic Hierarchy Process. In 1988 Berlin, Heidelberg. Springer.
52. Yeo S H, Neo K G, Tan H C, Assessment of health hazards in production of printed paper packages. *Int J Adv Manuf Technol* 1998; **14**:376–384.
53. Arslan O, Quantitative evaluation of precautions on chemical tanker operations. *Process Saf Environ Prot* 2009; **87**:113–120.
54. Boffetta P, Jourenkova N, Gustavsson P, Cancer risk from occupational and environmental exposure to polycyclic aromatic hydrocarbons. *Cancer Causes Control* 1997; **8**:444–472.
55. Gamble J F, et al. Exposure-response of asphalt fumes with changes in pulmonary function and symptoms. *Scand J Work Environ Health* 1999; **25**:186–206.
56. Estrela S, I publish, therefore I am. Or am I? A reply to A bibliometric investigation of life cycle assessment research in the web of science databases by Chen et al. (2014) and Mapping the scientific research on life cycle assessment: a bibliometric analysis by Hou et al. (2015). *Int J Life Cycle Assess* 2015; **20**(12): 1601–1603.
57. China NHFPC (National Health and Family Planning Commission), 'Zhongguo jumin yingyang yu manxingbing zhuangkuang baogao (2015 Nian) [Report on Chinese Residents' Chronic Diseases and Nutrition 2015]', 2016, Beijing: People's Medical Publishing House.
58. GBD 2016 Alcohol Collaborators, Alcohol use and burden for 195 countries and territories, 1990–2016: A systematic analysis for the Global Burden of Disease Study 2016. *Lancet* 2018; **392**(10152): 1015–1035.
59. Sturm R, The effects of obesity, smoking, and drinking on medical problems and costs. *Health Aff* 2002; **21**:245–253.
60. Blanc P D, et al. Occupational exposures and the risk of COPD: Dusty trades revisited. *Thorax* 2009; **64**:6–12.
61. Caldwell J A, Fatigue in aviation. *Travel Med Infect Dis*. 2005; **3**:85–96.
62. Williamson A M, Feyer A - M, Friswell R, The impact of work practices on fatigue in long distance truck drivers. *Accid Anal Prev* 1996; **28**:709–719.
63. Shappell S A, Wiegmann D A, The human factors analysis and classification system–HFACS. 2000, US Federal Aviation Administration, Office of Aviation Medicine.
64. Wiegmann D A, Shappell S A, Human error analysis of commercial aviation accidents: Application of the Human Factors Analysis and Classification System (HFACS). *Aviat Space Environ Med* 2001; **72**(11): 1006–1016.
65. Chan A P C, et al. Determining an optimal recovery time for construction rebar workers after working to exhaustion in a hot and humid environment. *Build Environ* 2012; **58**: 163–171.
66. Shikdar A A, Sawaqed N M, Worker productivity, and occupational health and safety issues in selected industries. *Comput Indust Engng* 2003; **45**:563–572.
67. Rowlinson S, et al. Management of climatic heat stress risk in construction: A review of practices, methodologies, and future research. *Accid Anal Prev* 2014; **66**: 187–198.
68. Pilcher J J, Nadler E, Busch C, Effects of hot and cold temperature exposure on performance: A meta-analytic review. *Ergonomics* 2002; **45**(10): 682–698.

69. Agrawal Y, Platz E A, Niparko J K, Risk factors for hearing loss in US adults: data from the National Health and Nutrition Examination Survey, 1999 to 2002. *Otol Neurotol* 2009; **30**: 139–145.
70. Dobie R A, The burdens of age-related and occupational noise-induced hearing loss in the United States. *Ear Hear* 2008; **29**:565–577.
71. Nelson D I, et al. The global burden of occupational noise-induced hearing loss. *Am J Indust Med* 2005; **48**:446–458.
72. Chan A P C, et al. Using the thermal work limit as an environmental determinant of heat stress for construction workers. *J Manage Enginng* 2013; **29**:414–423.
73. Gatchel R J, Schultz I Z, *Handbook of musculoskeletal pain and disability disorders in the workplace*. 2014: Springer.
74. Torma-Krajewski J, et al. *Ergonomics and Risk Factor Awareness Training for Miners*. 2008, U.S. National Institute for Occupational Safety and Health (NIOSH): Pittsburgh Research Laboratory. Pittsburgh, PA.
75. Chan M, *Fatigue: The most critical accident risk in oil and gas construction*. 2011; **29**:341–353. Construct Manage Econ
76. Madaan J, Mangla S, Decision modeling approach for eco-driven flexible green supply chain, in *Systemic Flexibility and Business Agility*. 2015, Springer. 343–364.
77. Connor T H et al., NIOSH alert: preventing occupational exposures to antineoplastic and other hazardous drugs in health care settings. 2004, DHHS (NIOSH) Publication Number 2004—165:U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.
78. Landen D.D. et al., Injuries, Illnesses, and Hazardous Exposures in the Mining Industry, 1986-1995: A Surveillance Report. 2000, U.S. Department of Health and Human Services Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: Washington, DC.

Appendix:

A four-step backward search strategy, proposed for improving both precision and recall simultaneously [18, 19], was adopted in this study.

In step 1, search was conducted in two comprehensive databases—Scopus and WOS—for tentatively identifying the results of the relevant subject published in mainly peer-referred journals. The used query was TS = ((((‘occupational’) AND (((‘health’) OR (‘hazard*’) OR (‘disease*’)))) OR (‘industrial hygiene’)) AND (((‘highway*’) OR (‘road*’) OR (‘pavement*’)) AND (‘construct*’))).

In step 2, titles, keywords and abstracts were scanned for identifying the synonyms for the word ‘occupational health’. For instance, it was found that NIOSH uses several words such as ‘occupational exposure’, ‘occupational illness’, or ‘occupational injury’ as synonyms [77, 78]. Other synonyms include the term ‘health’, ‘disease’, ‘illness’, ‘sickness’, ‘exposure’, and ‘injury’ prefixed with the word ‘industrial’. The purpose of this step is to expand the keyword list for new search to further improve the Precision and Recall.

In step 3, renewed search was performed, using the query TS = (((((‘occupational’) OR (‘industrial’)) AND (((‘health’) OR (‘disease*’) OR (‘exposure*’) OR (‘ill*’) OR (‘injur*’) OR (‘hygiene’)))) OR (((‘occupational’) AND (‘hazard*’)) OR ((‘industrial’) AND (‘sick*’)))) AND (((‘highway*’) OR (‘road*’) OR (‘pavement*’)) AND (‘construct*’))). For WOS, the reference settings were restricted in Science Citation Index (SCI) Expanded and Social Science Citation Index (SSCI). A total of 252 and 57 publications were obtained after this step.

In step 4, the citation indices were imported into the software Endnote® for removing duplications. Book sections, conference proceedings and serials were also removed. After this selection, a total of 229 articles were retained. Based on the titles and DOIs of all the papers, another de-duplication was processed manually. At the end of the step, a total of 179 articles were retrieved.