Stakeholders' Perception on Pavement Life Cycle Assessment (LCA) in Canada

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Abstract

The integration of life cycle assessment (LCA) has become increasingly crucial in the Canadian pavement industry, primarily to address environmental and sustainability concerns. However, the practical application of LCA in pavement projects often faces obstacles such as a lack of expertise, methodological inconsistencies, and data inaccessibility. In this context, stakeholders' insights can be vital for identifying these barriers and their potential solutions for promoting sustainable pavement practices. This research primarily explored stakeholders' perceptions of LCA practices, methodologies, and technical features in Canada through a survey-based study. An online, semi-structured, and self-administered questionnaire was developed and distributed to the stakeholders via email and LinkedIn. Over a three-month period, 108 responses were received from the stakeholders, and after data screening, 93 responses were retained for reporting and analysis. The survey revealed substantial involvement of the Canadian pavement industry in sustainable pavement research and development activities, with a strong focus on LCA. Standard practices include the cradle-to-grave method, carbon footprint assessment, emphasis on sustainability concerns, and the incorporation of recycled materials. Although this survey highlighted the critical role of software tools in pavement LCA, it also identified data gaps, proprietary data issues, and a strong willingness to contribute to an open-source LCA data platform as significant outcomes. The time-consuming nature of LCA and limited data transparency were identified as major challenges that the respondents faced while conducting LCA for pavements. Finally, this study emphasized the need for standardized guidelines, improved data collection methods, and centralized data repositories to enhance the implementation of pavement LCA in Canada.

Introduction

In Canada, the transportation sector was the second-largest contributor to greenhouse gas emissions, accounting for 22% of the total emissions in 2022[1]. This substantial contribution underscores the critical need for strategies to reduce environmental emissions within this sector. Additionally, Canada has committed to reaching net-zero emissions by carrying out its expanded climate plan by 2050[2,3]. Therefore, an urgent and comprehensive approach is required, incorporating effective plans for emission reduction, stakeholder engagement, and implementation frameworks to support sustainable pavement practices.

Life cycle assessment (LCA) is a methodology for evaluating the environmental impacts of pavement systems throughout their life cycles[4]. Additionally, this enables the stakeholders to identify the most environmentally friendly options and implement strategies that reduce the overall carbon footprint of infrastructure[5]. As a result, the need for LCA frameworks is acute, especially in Canada, where diverse climatic conditions and extensive road networks pose unique environmental challenges[6].

However, the practical application of LCA in pavement projects faces several challenges, including data availability, methodological consistency, and integrating LCA findings into decision-making processes[7]. Stakeholders often struggle to access reliable and specific data necessary for a comprehensive LCA[8]. Additionally, inconsistent methodologies complicate the integration of LCA findings, resulting in variable results and a lack of standardization across projects[9]. Also, the tools used for LCA are often complex and not user-friendly, making the process time-consuming and difficult[10]. This is further exacerbated by inadequate training and insufficient documentation[11]. Moreover, stakeholder engagement is hindered by a general lack of familiarity and expertise with LCA methodologies, which impedes the effective implementation of sustainable practices[12].

To address these issues, insights from stakeholders can be crucial in the context of LCA for pavements. As the stakeholders possess practical knowledge and experience invaluable for identifying real-world challenges and needs, their insights can reveal specific issues that might not be evident through theoretical analysis alone[13]. Also, direct engagement of stakeholders ensures that the developed solutions are suitable for actual practice, making them more applicable and practical[14]. This inclusive approach fosters collaboration and enhances the relevance of LCA frameworks to ensure sustainable solutions for pavement projects[15].

Several studies highlighted the importance of stakeholders' inclusion through surveys in improving LCA practices. Backes and Traverso identified critical components for advancing life cycle sustainability assessment (LCSA) implementation and interpretation, such as a comprehensive baseline LCSA framework and early stakeholder involvement, by surveying sustainability experts globally[16]. Also, Bruce-Hyrkäs et al. assessed the opportunities and obstacles of conducting LCA within the building sector. They found that integrating building information modeling (BIM) with LCA improves efficiency throughout the design process despite its currently limited implementation[16]. Again, Schlanbusch et al. highlighted that performing building LCA is often time-consuming and expensive, emphasizing the need for simplified tools and predefined default values[9]. Similarly, Jusselme et al. identified the limited use of LCA software due to its inefficiency and incompatibility with the design process and suggested the need for more user-friendly and interoperable tools[15]. Balouktsi et al. highlighted that a lack of legislation leads to insufficient client demand for LCA, which impedes the development of expertise and efficient assessment processes. Olinzock et al. highlighted that despite high awareness of sustainability, the actual use of LCA remains limited due to its complexity, cost, and lack of client demand[12]. These studies collectively demonstrate the critical role of stakeholders in identifying practical challenges and informing the development of effective LCA tools and frameworks. Therefore, by capturing diverse perspectives and specific needs, surveys can guide the creation of more applicable and efficient solutions to enhance the adoption of LCA practices in the pavement sector.

In this context, through a comprehensive survey, this research aims to assess stakeholders' perceptions on applying LCA in Canadian pavement projects. This survey-based study is the first of its kind globally in the field of LCA for pavements. The survey targets diverse stakeholders and experts, including professionals from transportation agencies, industry or association representatives, environmental or sustainability consultants, regulatory compliance enforcers, academic researchers, and policymakers. The inclusion criteria focus on individuals directly involved in the pavement industry and its associated sectors. Exclusion criteria apply to those not actively engaged in these sectors or lacking direct professional experience. By gathering detailed insights directly from stakeholders, this survey aims to identify the practical challenges and data gaps hindering the effective implementation of LCA in pavement projects. The results will also provide valuable feedback for enhancing methodological consistency, improving data reliability, and developing user-friendly LCA tools. Therefore, this research will ultimately assist policymakers and industry professionals in integrating sustainable strategies into pavement projects to reduce environmental impacts effectively.

Objectives

The primary objective of this study is to assess the current practices, methodologies, and tools adopted by Canadian government transportation agencies and pavement industries for implementing pavement LCA. By evaluating these parameters, this study aims to understand the prevailing standards and identify

the best practices adopted across the organizations. This comprehensive assessment will provide a clear picture of the existing landscape and its effectiveness for pavement LCA in Canada.

Another critical objective is to identify the challenges faced during pavement LCA application and gather stakeholder insights on potential solutions for these challenges. This feedback will pinpoint the critical points of concern in the current system and propose actionable solutions to overcome these barriers. Successful attainment of these objectives will reflect the stakeholders' vision for the future improvement, expansion, and areas of enhancement for pavement LCA in Canada.

Methodology

This study aims to represent the stakeholders' perceptions of LCA in the Canadian pavement industry. The responses were collected through an online, semi-structured, and self-administered questionnaire conducted between December 2023 and March 2024. Before developing the questionnaire, a detailed literature review was conducted to gather essential background information on LCA for pavements.

Following the primary literature review, online interviews were conducted with academic and industry professionals who have been involved in pavement research for over thirty years to ascertain the relevance and comprehensiveness of the study. These experts were from reputable Canadian organizations, including the Ontario Asphalt Pavement Council (OAPC), the National Research Council Canada (NRC), the City of Ottawa, the City of Toronto, and the Ontario Ministry of Transportation (MTO). Initially, twenty-seven questions were developed based on the literature review and expert opinions. These questions were then assessed in three steps by the research group members of the Advanced Road and Transportation Engineering Lab (ARTEL) at Carleton University, Canada. This rigorous process ensured that the final questionnaire was robust and targeted the most relevant issues in pavement LCA.

Structure of the Questionnaire

The finalized questionnaire consisted of eighteen questions organized into five distinct sections. The sections and their respective contents are as follows:

Section I: Survey demographics
Section II: Sustainable pavement research and significance of LCA in pavement projects
Section III: Current state, implementation, and practices of LCA for pavements
Section IV: Challenges associated with life cycle assessment of pavements
Section V: Potential solutions for the associated challenges

The questionnaire incorporated a combination of multiple-choice questions, open-ended questions, and the ranking of essential factors. A five-point Likert scale was used to rate the challenges associated with pavement LCA and their potential solutions. Except for the Likert scale questions, all other questions included an open-text option for experts to provide their thoughts and concerns regarding various aspects of pavement LCA. Additionally, a comment section at the end of the questionnaire invited experts to share their experiences, expectations, and suggestions on LCA for pavements.

Survey Implementation and Response Rate

After preparing the draft questionnaire and protocol requirements, all documents were submitted to the Carleton University Research Ethics Board-B (CUREB-B) for final approval. Once ethical approval was

granted (Project #120550), the survey was created using Qualtrics software. Simultaneously, contact information for stakeholders was collected from their publicly available profiles, research websites, and publications. Following this, an email invitation containing a survey link was sent to these experts in the field of pavement engineering.

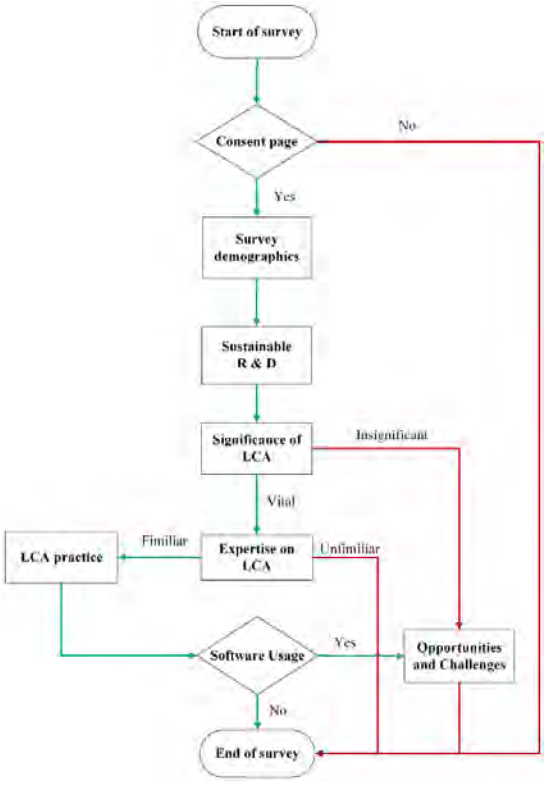
Participation in this survey was voluntary, allowing participants to opt-out or skip any questions they did not wish to answer. They could request that specific responses be excluded from the final analysis and had the right to withdraw their participation from the survey at any time before submitting the survey form. However, since the survey was anonymous, withdrawal was impossible once a response was submitted. Research records may be accessed by the Carleton University Research Ethics Board to ensure ongoing ethics compliance.

The survey details and participation links were also shared on LinkedIn to reach a broader audience of professional networks. The stakeholders were also requested to forward the survey to their peers from the pavement industry and related organizations. Data collection continued for three months, during which reminder emails were sent to participants to maximize responses. A total of 605 emails were sent to potential pavement experts; 108 responses were received, of which 93 were retained as valid after data screening. This provided a response rate of slightly more than 15%, which is considered satisfactory for this type of study.

Survey Framework

The survey was meticulously structured to ensure an interactive and engaging experience for the respondents. Figure 1 illustrates the survey framework used in this study.

Figure 1. Survey framework



The survey started with a "Consent Page," which is a fundamental ethical requirement in research involving human participants. On this page, the participants were informed about the details of the study, their rights as participants, and the confidentiality of their responses. Following this, the demographic information of the stakeholders was collected to understand the diversity of the responses. The survey then advanced to the sustainable pavement research and development efforts of Canadian transportation agencies and the pavement industry, followed by the perceived significance of LCA in pavement projects. If respondents indicated that LCA was "insignificant" to their pavement projects, they were directed to the "Opportunities and Challenges" section and subsequently to the end of the survey. Otherwise, they would be taken to the next section. Participants were next asked about their expertise in LCA. Those unfamiliar with LCA were directed to the end of the survey. For those familiar with LCA, detailed questions about LCA practices, methodologies, and software usage followed. If they indicated their proficiency with software, they were routed to "Opportunities and Challenges." Finally, the survey concluded with a thank-you note, emphasizing the importance of their participation and contributions to the research. This structured flow supported comprehensive data collection, facilitating a thorough analysis of LCA practices and their impact across various sectors.

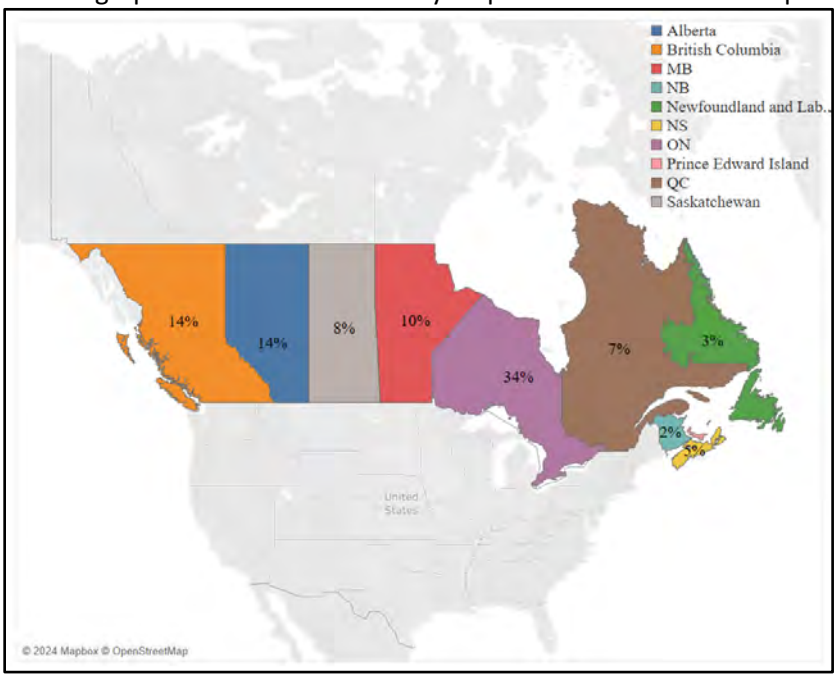
Major findings

Survey demographics

Geographic distribution

Figure 2 represents the geographic distribution of survey respondents over ten Canadian provinces. The map illustrates that the highest proportion of responses was obtained from Ontario (34%). This substantial involvement likely reflects the concentration of academic institutions, research facilities, and industry stakeholders practicing pavement LCA in this province.

Figure 2. Geographic distribution of survey respondents over Canadian provinces



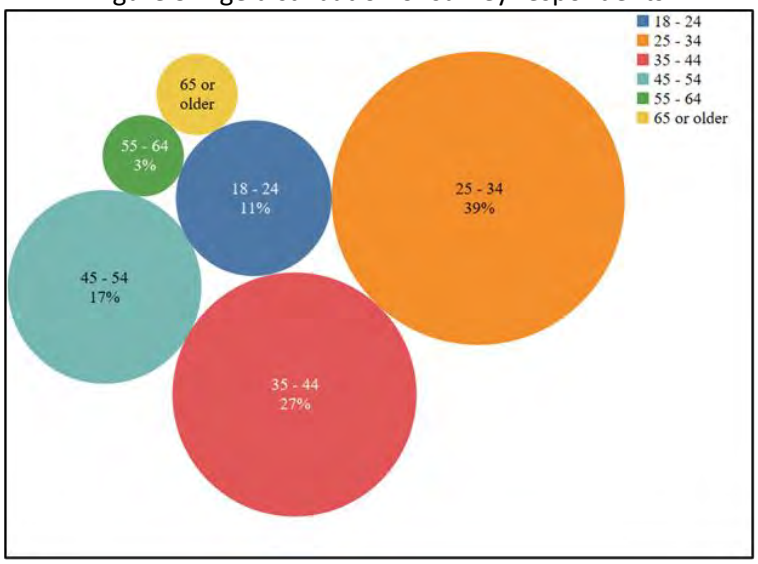
Both British Columbia and Alberta showed a substantial contribution, each representing 14% of the total respondents. Saskatchewan accounted for 10% of the respondents, and Manitoba for 8%, indicating notable engagement considering their smaller populations compared to provinces such as Ontario and British Columbia. Quebec accounted for 7% of the responses, potentially reflecting its growing focus on sustainability in the transportation sector. The responses from Nova Scotia, New Brunswick, Newfoundland and Labrador, and Prince Edward Island were 5%, 2%, 3%, and 3%, respectively, possibly due to their smaller sizes and populations and the limited number of experts within the scope of the survey.

Age

The bubble chart in Figure 3 displays the age distribution of the respondents, divided into six groups. The size of the bubbles represents the proportion of the respondents within each age group.

The figure shows that the highest proportion of responses (39%) was obtained from the age group 25-34. This indicates that most respondents are at the early to mid-career level and engaged in active practices on LCA for pavements. The second-largest age group, 35-44 years, represents 27% of responses, followed by the age group 45-54 with 17% of responses. These proportions likely include individuals with substantial professional experience who shared their extensive expertise in the survey. With 11% of the responses, the age group 18-24 is typically composed of young professionals or students, indicating a growing interest in the subject among young professionals. Participants aged 55 or older contributed the remaining 6% of responses. Overall, the responses from all age groups signify the inclusion of stakeholders from different career stages, enriching the survey outcomes with various experiences and viewpoints.

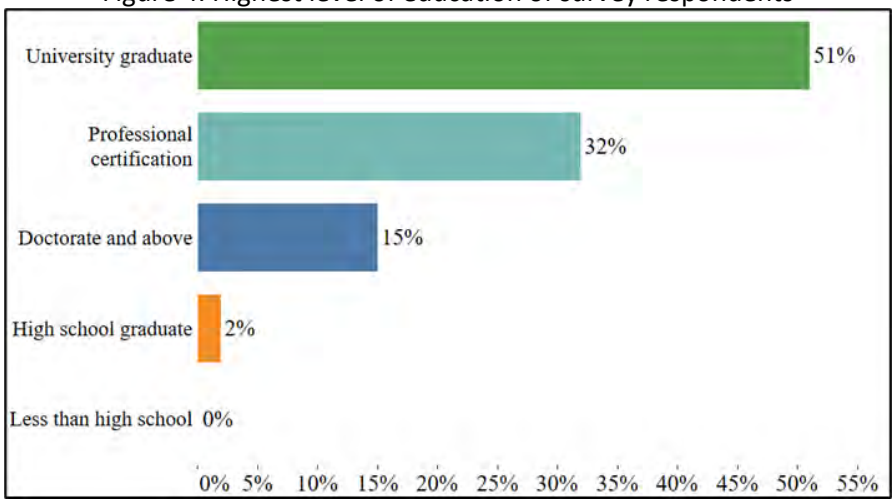
Figure 3. Age distribution of survey respondents



Education

The highest level of education of respondents helps establish that the survey data are credible, relevant, and representative of the expertise of the targeted population on LCA for pavements. The bar chart in Figure 4 illustrates the highest academic qualifications of the stakeholders who responded to the survey.

Figure 4. Highest level of education of survey respondents

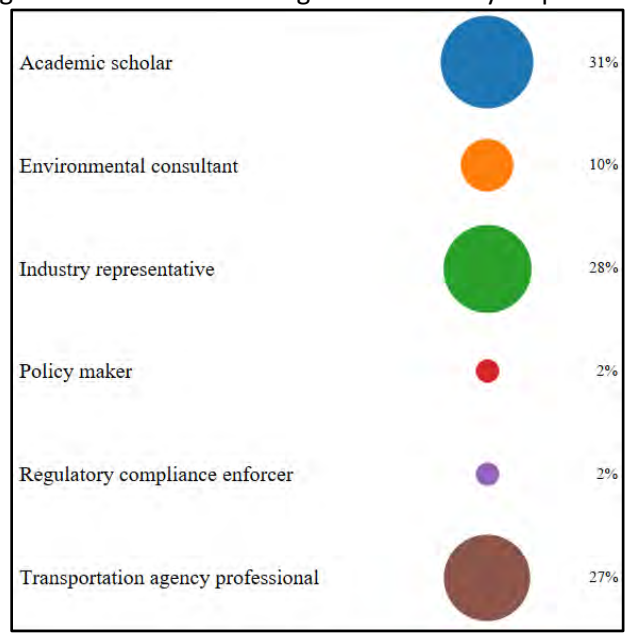


Professional background

Figure 5 represents the professional affiliations of the survey respondents, which is necessary to support the development of targeted and practical recommendations.

In this survey, 31% of respondents were academic scholars who provided their valuable research-based insights on pavement LCA. Industry representatives accounted for 28% of responses, followed by transportation agency professionals (27%). The responses from these two groups are vital as they can reflect the field practice of LCA concerning pavement design, construction, and management.

Figure 5. Professional background of survey respondents

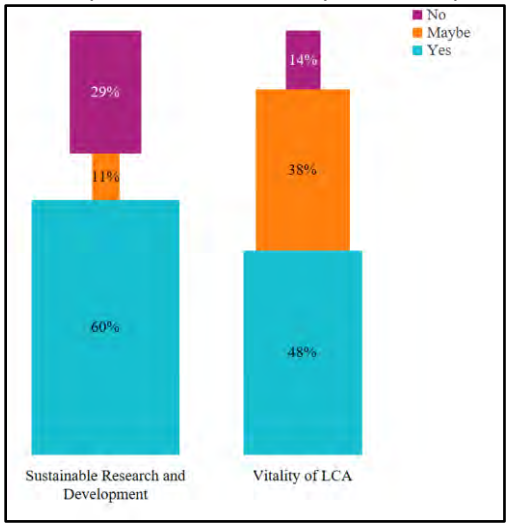


Environmental consultants comprised 10% of the respondents, which is significant for understanding the environmental impacts and sustainability thinking of pavement LCA. A small proportion of responses came from regulatory compliance enforcers (2%) and policymakers (2%). Although small in number, their participation is critical as they influence decision-making and provide a compliance perspective to the survey.

Institutional involvement in sustainable pavement research and development

The stakeholders were asked whether their corresponding institutions were involved in sustainable pavement research and development activities. The responses are illustrated in Figure 6.

Figure 6. Sustainable practices and vitality of LCA in pavement projects



Most of the participants (60%) responded positively and indicated that their corresponding institutions were involved in sustainable pavement research and development activities. However, nearly one-third of the respondents reported no active involvement in sustainable pavement research and development in their organizations. Also, 11% of stakeholders were uncertain, suggesting a potential for future engagement in sustainable research and development but currently lacking active involvement.

Vitality of life cycle assessment

The stakeholders were also asked whether LCA is a vital aspect of their pavement projects. An overview of the responses is depicted in Figure 6. Nearly half of the respondents acknowledged the vitality of LCA in their projects. However, 14% of the respondents indicated that LCA is not considered a significant issue in their projects. Moreover, a considerable percentage of respondents (38%) were neutral, suggesting awareness of LCA in their projects, although its implementation has yet to be fully established.

Figure 6 also reveals a significant outcome of this study, a proportional relationship exists between institutional involvement in sustainable research and development and the vitality of LCA in pavement projects. Institutions that actively participate in sustainability through research and development are more likely to value and implement LCA. These responses also emphasize the necessity of promoting and implementing sustainable practices in pavement infrastructure development.

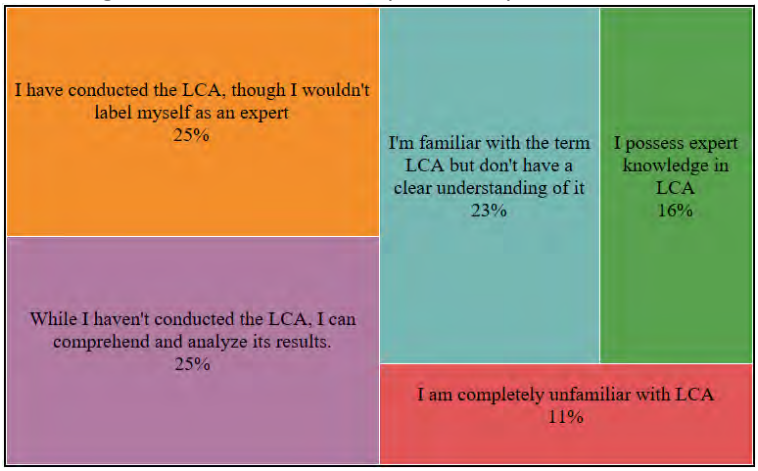
Current state, implementation, and practices of LCA

Examining the current state and practices of LCA in the pavement sector reveals the level of expertise among professionals, critical environmental aspects, standard methodologies in use, priority areas of concern, and approaches to promoting resilience. The outcomes of these aspects assist the pavement industry in continuous improvement and innovation in pursuing more sustainable and effective pavement solutions.

Expertise in LCA

The stakeholders' levels of expertise with pavement LCA are presented in Figure 7. The data shows that 16% of participants identified themselves as experts in LCA. This group likely plays a significant role in leading and guiding LCA practices within their organizations.

Figure 7. Stakeholders' expertise in pavement LCA



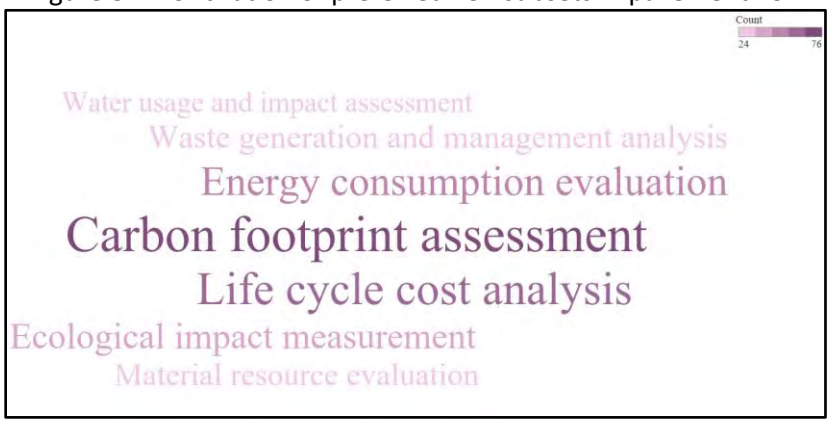
A quarter of the respondents had practical experience conducting LCA but did not consider themselves as experts. Additionally, another 25% of respondents reported their ability to understand and analyze LCA results without having conducted one independently. Moreover, one-fourth of the respondents were familiar with LCA but lacked a clear understanding. However, a notable minority (11%) was completely unfamiliar with LCA. The data infers that although stakeholders have a substantial base of practical and theoretical knowledge on pavement LCA, continuous education and skill development in LCA for the stakeholders in the roadway infrastructure sector are also needed.

Preferred LCA subsets

In this question, the respondents were asked to rank the LCA subsets they had employed in their pavement projects, and Figure 8 represents the outcomes. The respondents were allowed to select all applicable subsets, providing a comprehensive overview of the most commonly used LCA components. According to the data, carbon footprint assessment was the most frequently employed LCA subset, with 76 counts. Life cycle cost analysis (LCCA) and energy consumption evaluation closely followed carbon footprint assessment with 65 and 51 counts, respectively. After that, the stakeholders mentioned that they had been using pavement LCA to measure ecological impact, waste generation and management

analysis, material resource evaluation, and water usage and impact assessment subsequently. These responses reveal that the stakeholders of the pavement industry strongly emphasize assessing and mitigating carbon footprints and energy consumption alongside conducting LCCA. These practices will ensure a resilient pavement infrastructure, which is environmentally, economically, and socially sustainable.

Figure 8. Prioritization of preferred LCA subsets in pavement LCA

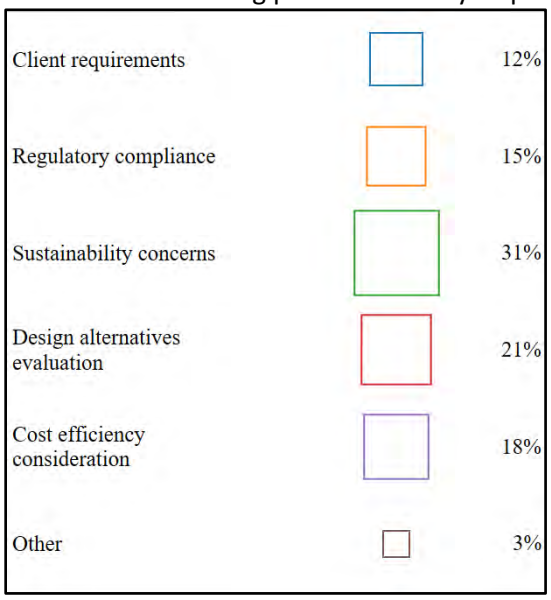


Rationale for assessing the life cycle performance

When the stakeholders were asked about the motivations behind assessing the life cycle performance of pavement designs, 31% indicated that "sustainability concerns" motivated them to assess the pavement life cycle performance (Figure 9).

More than one-fifth of the participants mentioned the scope of design alternatives evaluation, followed by life cycle cost analysis (18%). Regulatory compliance and client requirements motivated 15% and 12% of respondents, respectively, to conduct LCA for their pavement projects.

Figure 9. Rationale for assessing pavement life cycle performance

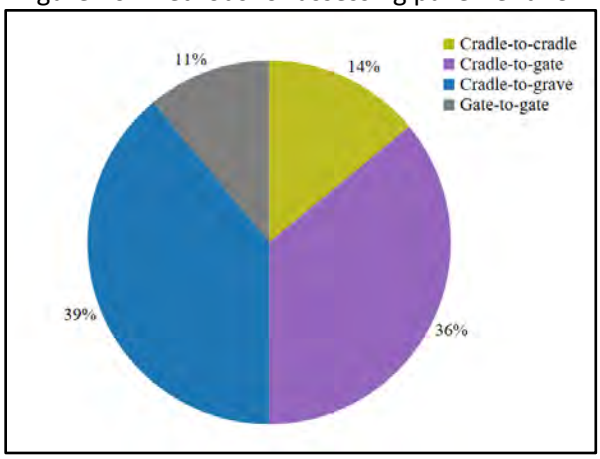


A small percentage (3%) selected 'Other,' indicating various unspecified reasons for using LCA. The outcome of this segment closely aligns with global efforts to mitigate climate change impacts and promote sustainable development. It is also notable that, to foster pavement LCA, proper emphasis should be put on addressing regulatory compliance and client requirements. This action will not only ensure legal adherence and environmental accountability but also help meet client expectations.

Methods for conducting pavement LCA

Different LCA methods signify the consideration of relevant stages of the pavement life cycle, ensuring standardization and comparability over projects or studies. Figure 10 represents a pie chart that illustrates various methods practiced by respondents for conducting pavement LCA.

Figure 10. Methods for assessing pavement LCA



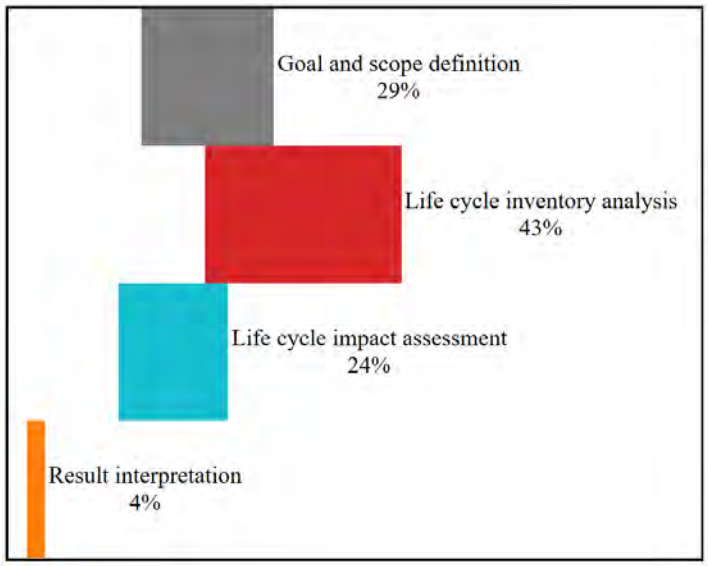
Most commonly, the cradle-to-grave approach was used by 39% of respondents, followed by the cradle-to-gate method (36% of respondents). As 14% of respondents mentioned, the cradle-to-cradle method was the next one, which generally emphasizes the recycling or reuse of materials at the end of their life cycle. The least utilized method, selected by 11% of respondents, was gate-to-gate. This approach focuses on a specific part of the life cycle, typically the manufacturing process. Notably, the selection of cradle-to-grave and cradle-to-gate methods highlights a preference for comprehensive life cycle analysis that provide a broad understanding of environmental impacts. Besides, the growing use of cradle-to-cradle reflects an increasing focus on circular economy practices.

Most challenging step in pavement LCA

Generally, the LCA process is structured into four critical steps, i.e., goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and result interpretation. Each step serves a specific function to ensure a thorough and accurate assessment. When the stakeholders were asked to indicate the primary step that they found most challenging to comprehend, most respondents (43%) reported life cycle inventory analysis as the most challenging one (Figure 11). Generally, this step involves the comprehensive data collection and analysis of all inputs and outputs throughout the pavement's life cycle. The complexity may arise from gathering detailed and accurate data, often from various sources, which can be time-consuming and resource intensive. Again, 29% of respondents listed defining the goal and scope as the most challenging for them. The difficulty here likely comes from the need to precisely define the system boundaries and functional parameters. About one-fourth of the stakeholders reported that they mainly struggled with the life cycle impact assessment step. As this phase involves evaluating the

potential environmental impacts based on the inventory data collected, stakeholders often find this analytical phase challenging due to its technical nature. Lastly, only 4% of respondents considered the result interpretation step the most challenging, which involves analyzing and drawing conclusions from the LCA results. Overall, the data reveals significant challenges the stakeholders face while conducting LCA, particularly in data collection and setting the goals and scope. Addressing these challenges through improved data management practices, guidelines for setting system boundaries, and enhanced technical expertise is crucial for ensuring the effectiveness and reliability of LCA in pavement.

Figure 11. Identification of most challenging steps for conducting pavement LCA

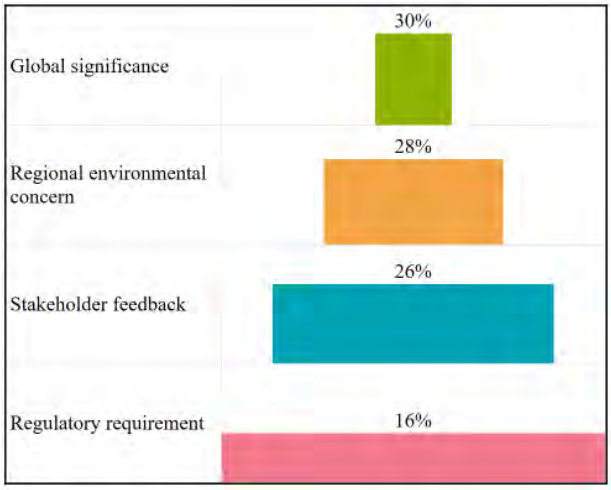


Prioritizing impact categories

Prioritizing impact categories allows the stakeholders to allocate the resources more efficiently. It enhances transparency and accountability, providing a rationale for selecting specific impact categories. Figure 12 illustrates the prioritizing techniques employed by the stakeholders while selecting the life cycle impact categories.

The data reveals a strong emphasis on global significance among 30% of stakeholders, indicating that the respondents prioritized environmental impacts with widespread implications, such as global warming potential. Close behind, regional environmental concerns were also highly prioritized (28%), reflecting the importance of addressing specific local environmental issues like smog potential. Moreover, 26% of stakeholders emphasized incorporating perspectives from clients, local communities, and environmental groups to ensure that the selected impact categories reflect their priorities. Lastly, 16% of respondents selected the categories based on the regulatory requirements. Overall, this distribution highlights a balanced approach to selecting impact assessment categories, considering both global and local environmental factors and the input from stakeholders and regulatory bodies.

Figure 12. Measures to prioritize impact categories by stakeholders



Sustainable pavement techniques

Sustainable pavement techniques are able to minimize resource extraction, reduce energy consumption, and decrease greenhouse gas emissions from pavement projects, all of which are critical in LCA. As a result, stakeholders are anticipated to utilize LCA to assess the feasibility of using these sustainable pavement techniques.

Figure 13. Stakeholders' feedback on sustainable pavement techniques

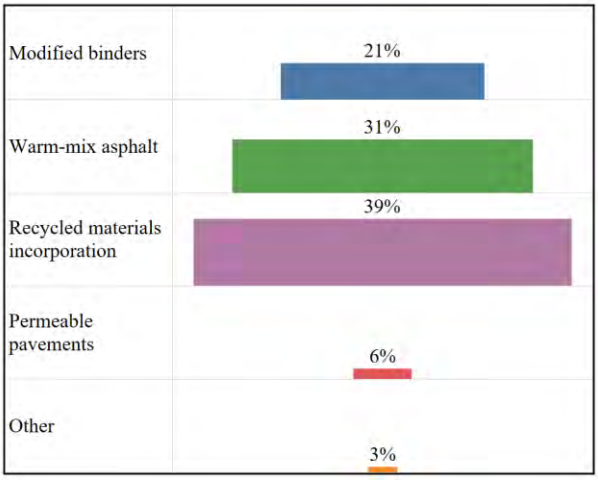
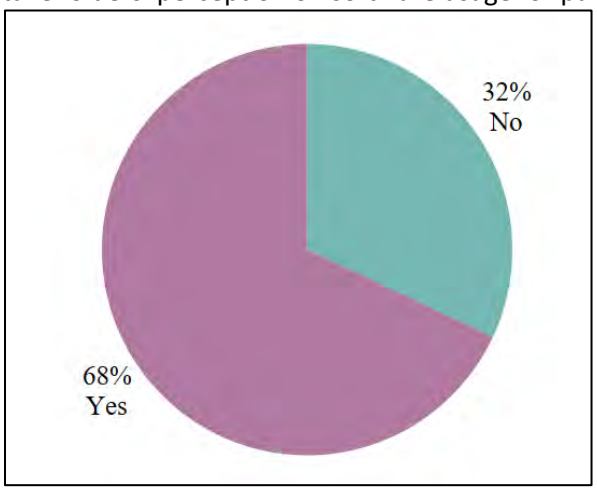


Figure 13 presents the sustainable techniques that stakeholders utilize most in LCA for pavements. The data reveals that incorporating recycled materials is the most practiced technique employed by 39% of respondents. This high percentage signifies the industry's commitment to recycling, reusing, and reducing virgin materials. Warm-mix asphalt (WMA) was the second most commonly utilized technique used by 31% of stakeholders. This high proportion highlights the benefits of WMA in reducing energy consumption and greenhouse gas emissions during pavement construction. Additionally, 21% of respondents reported using modified binders primarily as a sustainable pavement alternative in LCA. However, only 6% of respondents carried out permeable pavements, likely due to the complex nature of design and analysis in software. Surprisingly, 3% of respondents reported using other sustainable techniques, indicating a diversity of approaches and innovations in the industry.

Software usage for pavement LCA

In pavement design and management practice, the integration of LCA has become increasingly crucial in facilitating environmental conservation and economic efficiency. At the core of this advancement, the software tools act as a key component that bridges the gap between complicated environmental data and actionable insights. Understanding the significance of software usage for pavement LCA is vital for ensuring accurate, efficient, and reliable environmental assessments. Therefore, the respondents were asked whether they used software tools for conducting pavement LCA. According to Figure 14, 68% of the respondents confirmed that they had been using software tools, while 32% indicated that they had not yet used them.

Figure 14. Stakeholders' perception on software usage for pavement LCA

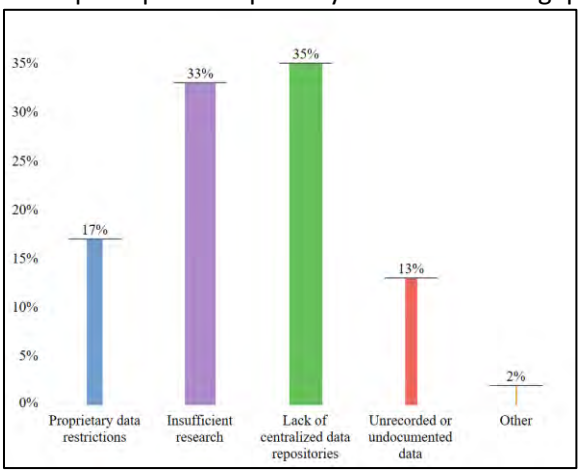


This high percentage of 68% indicates a significant shift towards technological advancements like software usage for LCA in the pavement industry. This shift is likely due to the need for the establishment of more reliable and comprehensive decision-making criteria that align with sustainability targets. However, the 32% who have yet to use these tools may face barriers such as lack of access to software, insufficient training, or technological constraints. Addressing these issues through increased training programs, more accessible software options, and technical support could further enhance the involvement rate.

Primary reason for data gaps

Any missing or incomplete data can significantly undermine the accuracy and reliability of LCA. When stakeholders were asked for their expert opinions on the primary reasons for data gaps in pavement LCA, the responses highlighted several key issues (Figure 15). The most significant factor identified was the lack of centralized data repositories, with 35% of respondents indicating this as a significant challenge. Again, 33% of stakeholders reported that insufficient research was another primary reason for data gaps in Canada.

Figure 15. Stakeholders' perception on primary reason for data gaps in pavement LCA

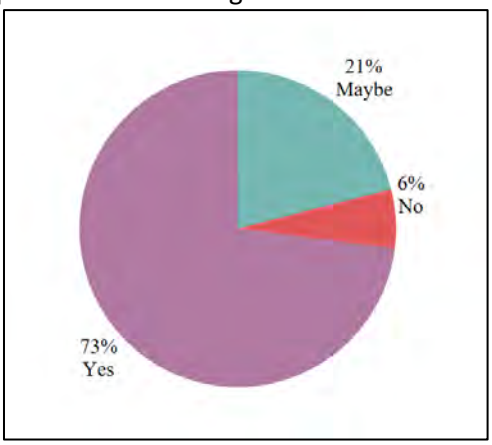


This highlights the need for more extensive and detailed studies to provide the necessary data inventory for accurate LCA. Additionally, 17% of participants indicated proprietary data restrictions as a notable concern, which signifies that confidentiality and competitive concerns limit the availability of essential data. Furthermore, unrecorded or undocumented data was identified by 13% of respondents. Lastly, 2% of respondents mentioned other unspecified reasons for data gaps, suggesting various additional factors that may contribute to the issue.

Willingness to contribute to an open-source data platform

The stakeholders were asked whether they wanted to contribute to an open-source pavement LCA data inventory. Figure 16 shows that a substantial portion (73%) of respondents expressed a strong willingness to contribute to an open-source data platform.

Figure 16. Stakeholders' perception on their willingness to contribute to an open-source data platform

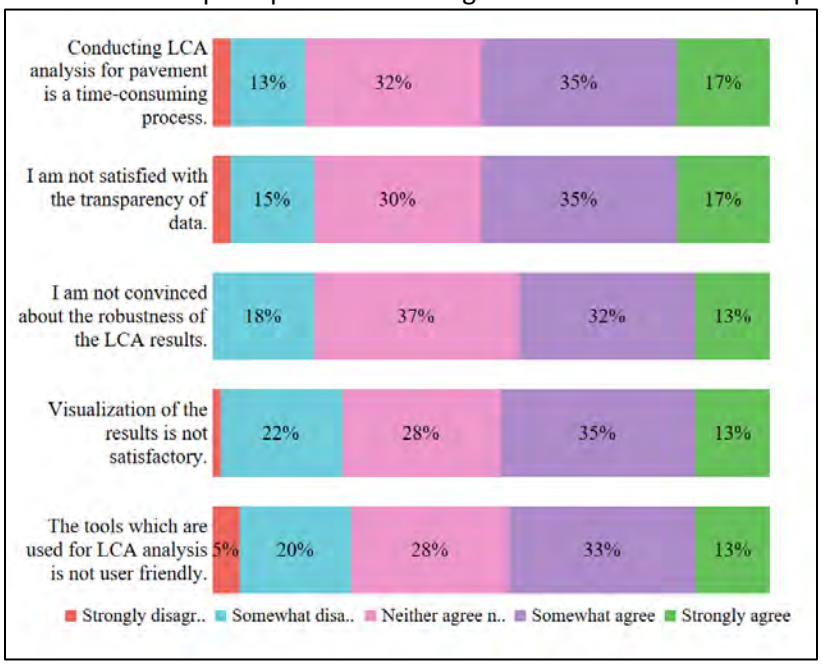


This positive response indicates a recognition of the need for, and the collective benevolence that can be achieved through an open-data inventory. Again, 21% of respondents indicated a conditional willingness to contribute, reflecting concerns about data privacy, transparency, and the need for clear guidelines and protocols. However, a minor but significant 6% of respondents expressed reluctance to contribute to an open-source platform. This reluctance may be driven by concerns about potential misuse of data, proprietary information, misleading interpretation, and reputational risk.

Challenges associated with life cycle analysis of pavements

As a burgeoning area of pavement engineering, LCA may involve of various issues that can impact the efficacy and reliability of the analysis. To address these issues, at first, the most common problems associated with LCA for infrastructure were meticulously studied. Therefore, the viability of these matters concerning the pavement industry was assessed by asking the stakeholders about their experience while conducting LCA for pavement. The opinions were collected using a five-point Likert scale, ranging from strongly disagree to strongly agree. Specific scores (strongly disagree = 1 to strongly agree = 5) were then assigned to each level of agreement or disagreement, and the weighted average for each challenge was calculated. The importance of these challenges, based on weighted-average ranking, is presented in Figure 17.

Figure 17. Stakeholders' perception on challenges associated with LCA for pavement



The figure depicts that the most significant issue identified was the time-consuming nature of conducting LCA, with 52% agreeing with the statement. Meanwhile, 32% of respondents were neutral on this issue, and 16% disagreed with the concern. Following this, issues related to data transparency were also highlighted, where 52% of respondents expressed their dissatisfaction. On the other hand, 30% neither agreed nor disagreed, reflecting a moderate level of satisfaction towards current data practices. However, 18% respondents disagreed with the concerns about data transparency.

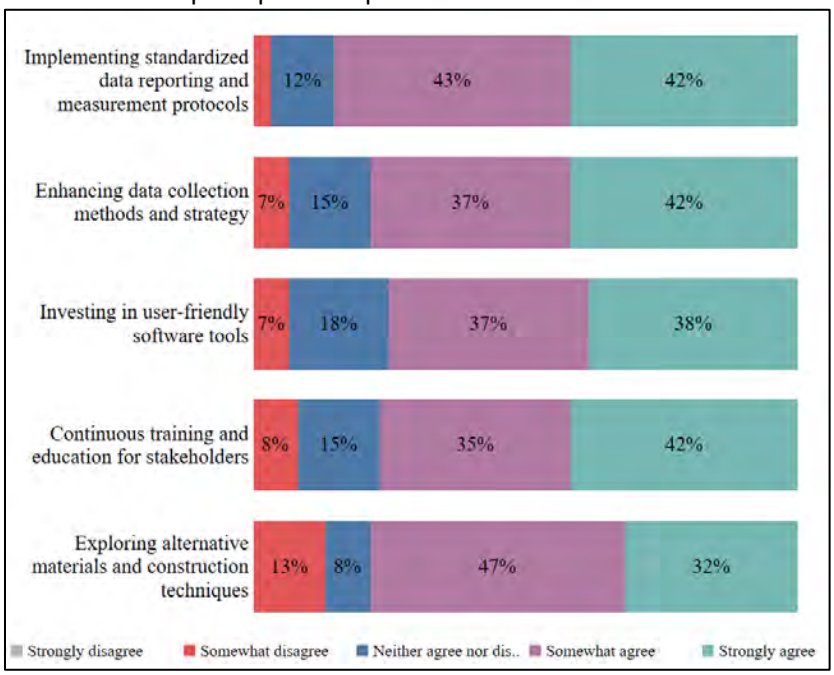
Issues about the robustness of LCA results were also significant, with 45% of respondents doubting the accuracy and reliability of the data. Furthermore, 37% of stakeholders held a neutral view of the robustness of LCA results, and 18% were comfortable with this issue. Additionally, the visualization of LCA results was another concern, with 48% of stakeholders indicating that current visualization methods are unsatisfactory. However, 28% of respondents neither agreed nor disagreed with the statement, and 24% were satisfied with the current methods of visualizing LCA results. Lastly, 46% of stakeholders found the tools used for LCA to be not user-friendly, suggesting that tool design and usability improvements are

necessary. Meanwhile, 28% of stakeholders expressed neutrality about the user-friendliness of LCA tools, whereas 25% found the tools manageable and effective for their respective purposes.

Potential solutions for the associated challenges

In this case, the stakeholders were requested to share their opinions on various potential solutions to address the challenges in pavement LCA. A five-point Likert scale, ranging from strongly disagree to strongly agree, was used to incorporate the perceptions. The weighted average for each solution was calculated after assigning a specific score (strongly disagree =1 to strongly agree=5) to each level of agreement or disagreement. Finally, the proposed solutions were ranked based on the weighted average, as illustrated in Figure 18.

Figure 18. Stakeholders' perception on potential solutions for the associated challenges



Implementing standardized data reporting and measurement protocols emerged as the most pressing solution, with 42% of respondents strongly agreeing and 43% somewhat agreeing. This reflects a significant stance on the need for standardized protocols to reduce variability in LCA results. Conversely, 12% were neutral, and no respondents disagreed, indicating minimal opposition to this proposal. Secondly, enhancing data collection methods and strategies was also highly supported, with 42% strongly agreeing and 37% somewhat agreeing. This solution can significantly improve the accuracy of LCA for pavement projects. Meanwhile, 15% of respondents neither agreed nor disagreed, suggesting a moderate level of neutrality, and only 7% somewhat disagreed. After that, investing in user-friendly software tools received strong support, with 75% agreeing. However, 18% of stakeholders were neutral, and 7% somewhat disagreed, indicating that while the majority support this initiative, a portion of the respondents are comfortable with the existing software tools. Following this, continuous training and education for stakeholders was supported by 42% of respondents who strongly agreed and 35% who somewhat agreed. This indicates the importance of educating stakeholders to understand LCA challenges through knowledge sharing. Nevertheless, 15% neither agreed nor disagreed, and 8% somewhat disagreed, showing some variance in opinions. Lastly, exploring alternative materials and construction

techniques was identified as another crucial solution, with nearly 80% agreeing. This highlights the stakeholders' belief in the potential of innovative materials and methods to mitigate the challenges in pavement LCA.

Summary and conclusions

This study has facilitated a comprehensive assessment of the current practices, methodologies, and technical features of implementing pavement LCA in Canada. A total of 93 experts from various Canadian transportation agencies, pavement industries, sustainability advisors, and academic scholars shared their experiences regarding pavement LCA to contribute to this study. This unprecedented study can significantly contribute to the decision-making process for stakeholders and ensure the proper allocation of resources to critical areas of improvement. The outcomes of this study can be summarized as follows:

- The majority of stakeholders are pavement experts from Ontario, primarily early to mid-career professionals. This notable presence of emerging professionals indicates a growing interest in pavement LCA among the young workforce. Academically, most respondents possess a high level of educational achievement, with many holding graduate degrees, including advanced professional or doctoral qualifications. Professionally, the survey included balanced expertise of academic scholars, industry representatives, and transportation agency professionals, ensuring comprehensive insights from various sectors involved in pavement design, construction, and management.
- The survey highlighted a strong involvement of government transportation agencies and pavement industries in sustainable pavement research and development activities, with many respondents indicating active engagement. Therefore, the vitality of LCA in pavement projects was acknowledged by nearly half of the respondents with some inconclusiveness, indicating room for potential improvement.
- The current practice demonstrates a strong awareness and commitment to environmental aspects, which is essential for effective LCA implementation in pavement. Carbon footprint assessment, LCCA, and energy consumption evaluation emerged as the most frequently employed LCA subsets, emphasizing environmental and economic sustainability significantly. Moreover, the stakeholders primarily used the cradle-to-grave and cradle-to-gate methods for LCA, reflecting a preference for comprehensive assessments.
- The survey also emphasized that sustainability concerns, design alternatives evaluation, and life cycle cost analysis are the primary drivers for assessing the life cycle performance of pavement. Furthermore, life cycle inventory analysis was identified as the most challenging step in the LCA process, followed by the goal and scope definition step. Addressing these challenges is crucial for improving the effectiveness of LCA. Also, stakeholders usually prioritize impact categories based on global significance and regional environmental concerns, ensuring a balanced approach.
- Although some stakeholders have a strong understanding and hands-on experience with pavement LCA, there is a need to enhance the expertise of the significant portion who lack familiarity or knowledge in this area through further education and training.
- The survey also addressed the critical role of software tools in pavement LCA. Many respondents stated their proficiency in software usage, reflecting a solid shift towards technological advancements in the pavement industry. This indicates issues related to proprietary information and confidentiality agreements within the organizations. Stakeholders also reported the lack of centralized data repositories and insufficient research as primary reasons for data gaps in LCA. Nevertheless, respondents were strongly willing to contribute to an open-source pavement LCA

data platform, which may lead to user-centric, efficient, and innovative LCA practices in the pavement industry.

- Among the significant challenges associated with LCA for pavement that this study showcased, the time-consuming nature of conducting LCA emerged as the most prominent one. Data transparency issues were also notable, with many stakeholders dissatisfied with current practices. Concerns about the robustness of LCA results were prevalent, and the visualization of LCA results was seen as inadequate by many respondents. The user-friendliness of LCA tools was another major issue, suggesting the need for improved training and educational facilities.
- To counteract these challenges, stakeholders strongly supported implementing standardized data reporting and measurement protocols to reduce the variability in LCA results. The stakeholders also focused on enhancing data collection methods and strategies. Additionally, exploring alternative materials and construction techniques was identified as a critical solution, demonstrating stakeholders' commitment to innovative techniques to address the challenges associated with LCA.

Overall, this study provided valuable insights that will guide software developers and policymakers in creating tools and procedures more aligned with the needs of pavement designers and stakeholders. Young professionals can use this study as a kickstart to learn about the latest methodologies, tools, and practices in LCA, enabling them to innovate and implement more environmentally friendly solutions in their pavement projects. Future research should focus on developing comprehensive databases and enhancing advanced LCA tools to support the industry's commitment to sustainable infrastructure development.

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