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ASSESSMENT OF LOCAL ENVIRONMENTAL IMPACTS IN CONSTRUCTION PROJECTS USING A KPI-BASED APPROACH

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Abstract

The construction sector is a major global source of environmental pollution, with significant direct and indirect impacts on the environment. Environmental aspects are divided into nine categories, one of which is local issues. Construction causes a multitude of local issues that serve as significant sources of environmental, social, and economic challenges for workers and nearby communities. The insufficient research works and systems for measuring the adverse effects of environmental concerns, both qualitatively and quantitatively, create significant challenges for effective environmental management. To address the challenges, this paper aims to propose a Key Performance Indicators (KPIs)- based approach to assess and analyze local environmental impacts in construction projects by identifying relevant indicators, integrating them into 4D workflows, and enabling data-driven decision-making for sustainable practices. By integrating environmental KPIs with 4D Building Information Modeling (BIM), the model dynamically reflects how each task affects the identified KPIs throughout the project schedule, influencing environment, community well-being, and economic performance over the project lifecycle. The proposed approach provides a holistic understanding of local concerns and facilitates stakeholder collaboration through shared and quantifiable metrics.

Keywords: building information modeling, construction projects, environmental impact assessment, key performance indicators, local issues.

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1. Introduction

The construction industry is a major contributor to environmental degradation, with significant direct and indirect impacts on surrounding communities and ecosystems. The Eco-Management and Audit Scheme (EMAS) categorizes environmental aspects into nine domains, including air emissions; water emissions; local issues; transport issues; effects on biodiversity; waste generation; incidents; use and contamination of land; and resource consumption [1]. While global sustainability goals have driven improvements in areas such as energy use and carbon emissions, local environmental issues, such as noise, dust, odor, and traffic disruption, continue to pose challenges in construction projects. These localized impacts are often underestimated or overlooked during early planning stages, despite their immediate and cumulative effects on the quality of life for nearby residents and on local economic activities. These issues, deeply intertwined with environmental, social, and economic well-being, require more structured and quantifiable methods for assessment and management.

In recent years, Key Performance Indicators (KPIs) have emerged as an effective means to measure, monitor, and manage sustainability performance across construction projects. According to Chan and Chan, KPIs are defined as a set of quantifiable measures used to monitor and evaluate critical success factors in construction projects, providing benchmarks to assess project performance across several dimensions such as time, cost, quality, environment, and safety [2]. Several studies have explored the role of KPIs in environmental management systems (EMS), sustainable design, and project delivery. However, the integration of environmental indicators into construction workflows, especially at the local scale, remains fragmented and underdeveloped. Moreover, traditional environmental assessment methods often lack the resolution to address the spatial and temporal variation of local impacts in a

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comprehensive and scenario-based manner. At the same time, 4D Building Information Modeling (BIM) has gained prominence as a powerful method for visualizing and coordinating construction processes across time and space, but its potential in environmental impact assessment remains underutilized.

To address these challenges, this paper aims to propose a KPI-based approach to assess and analyze local environmental impacts in construction projects by identifying relevant indicators, integrating them into 4D workflows, and enabling data-driven decision-making for sustainable practices. The local environmental, social, and economic impacts of construction projects will be identified through the literature review and environmental standards. These impacts would be translated into specific KPIs that could be quantified across different project scenarios. 4D BIM enables the analysis and comparison of environmental-oriented variants. The identified KPIs are then integrated into 4D BIM models and will be simulated across project variants. The 4D BIM model enriched with KPI data visualizes the evolving impact of each task on environmental, social, and economic factors, enabling comparative analysis across scenarios and the selection of the most sustainable project variant.

The findings are expected to provide a holistic understanding of interconnected local challenges while enabling measurable insights for local concerns. The application of KPIs within a BIM environment enables scenario testing and supports the iterative refinement of project plans. This approach highlights the importance of trade-offs between competing priorities, such as cost-efficiency and environmental sustainability, providing a foundation for more informed decision-making. Moreover, the proposed approach is expected to contribute to the standardization of environmental impact assessments by establishing transparent criteria. Finally, integrating KPIs into 4D workflows will foster stronger collaboration among stakeholders by providing a shared set of quantifiable metrics. The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on sustainability indicators and their application in construction, while Section 3 outlines the research approach. Section 4 presents a method to assess local issues across project variants using 4D BIM. Section 5 evaluates and validates the proposed method through a scenario-based paving project. Section 6 provides a discussion of the findings, and Section 7 concludes the paper and outlines directions for future research.

2. Related research

The necessity of effective environmental management in construction projects is underscored by the role of key KPIs in ensuring sustainability. KPIs serve as measurable benchmarks that guide the project management procedure, while aligning project objectives with environmental, economic, and social goals. In this context, Stanitsas et al. explored the integration of sustainability indicators into construction project management, identifying 82 relevant indicators categorized into economic (27 indicators), environmental (18 indicators), and social/management (37 indicators) dimensions [3]. Their study provides a structured approach for project managers to incorporate sustainability considerations. Similarly, Hřebíček et al. examined the role of KPIs in environmental management, emphasizing their significance in EMAS and International Organization for Standardization (ISO) 14001[4]. These studies collectively reinforce the critical link between structured management approaches and the effective application of sustainability-focused KPIs in construction. Moreover, a systematic approach to assessing environmental performance in construction relies on well-defined KPIs, which need to be identified and categorized through literature reviews to ensure their relevance within environmental assessment frameworks. Kylili et al. employed a review-based approach to examine KPIs in building renovations, emphasizing sustainability assessment through domains such as energy efficiency, waste reduction, and indoor environmental quality [5].

KPI-based frameworks are commonly applied in infrastructure projects to measure and manage their environmental performance in various aspects. Ugwu and Haupt developed a structured sustainability assessment method for infrastructure projects in the South African construction industry, categorizing sustainability into six dimensions—economy, environment, society, resource utilization, project management, and health and safety [6]. They employed Multi-Criteria Decision Analysis (MCDA) methods, including AHP and the weighted sum model, to compute a sustainability index for infrastructure projects. Similarly, Shen et al. developed a framework for evaluating infrastructure sustainability by identifying KPIs in environmental, social, and economic areas [7]. They surveyed three expert groups, including government officials, professionals, and clients, to assess the relevance of these KPIs. A scoring strategy was used to rank the indicators based on their importance across four different scenarios, helping to identify the most sustainable option. In addition, green construction relies on well-defined KPIs to monitor environmental performance on-site and across different construction methodologies. Pakzad et al. developed a framework of 16 key sustainability indicators for evaluating green infrastructure performance based on a literature review, semi-structured interviews with Australian experts, and a survey of national stakeholders, highlighting the connection between human well-being and ecosystem services [8].

Compared to 2D/ 3D technologies, 4D modeling enables practitioners to fully simulate and analyze the environmental impacts on workers, residents, and the public. The challenges of assessing the significance of environmental impacts, including impact assessment criteria such as scale, impact duration, type, severity, size, and frequency [9], and collaborative difficulties between stakeholders [10], can be overcome by leveraging 4D BIM procedures. Several studies have proposed 4D-based methods for modeling environmental impacts in construction projects. Ngbana et al. developed a structured and methodological approach for using 4D BIM to support environmental variant analysis in road construction projects, as horizontal structures [11]. Furthermore, Zanen et al. developed a 4D Computer-Aided Design (CAD) modeling approach to visualize the environmental impacts of a highway project on the public [12]. To support onsite monitoring of environmental impacts and enhance collaboration in environmental planning, Jupp proposed a schematic diagram of an overall 4D environmental planning and management process [9]. However, the current research works have not integrated KPIs of local issues in the 4D simulation process. In order to achieve this goal, local KPIs should be identified and the sources of these local issues should be identified and simulated with attention to their extent and significance on their receptors. Amrollahibuki and Boton identified the main sources and receptors of several significant local issues such as noise, vibration, and dust [13]. The indicators for common local issues of the construction projects are defined in the following sections, which is followed by modeling these impacts along with their sources and receptors in the 4D BIM by considering their related KPIs.

3. Research approach

This study follows a structured research approach consisting of three main phases, as demonstrated in Fig. 1. To understand the problem space, the study began with a review of the literature, environmental standards, and a search in the database. Several research gaps were identified based on this review, as discussed in Section 2, including the lack of a comprehensive method to assess local environmental impacts of construction projects across different project scenarios. These gaps emphasize the need to define common local indicators, simulate project variants in a 4D BIM environment, and assess their environmental impacts using quantifiable KPIs.

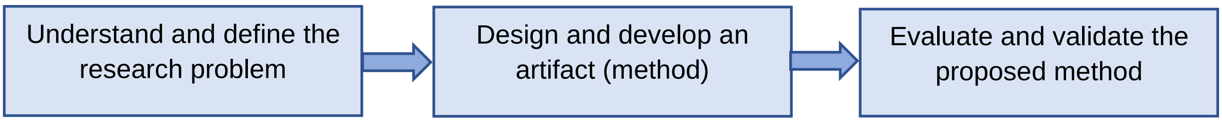


Fig. 1. The proposed research approach.

Based on the research gap, the study proposes a KPI-based approach aimed at integrating localized impact assessment within a 4D BIM environment, as detailed in Section 4. The third phase focuses on validating the proposed method through a scenario-based evaluation designed to assess its applicability and effectiveness, as discussed in Section 5. This evaluation aims to demonstrate how the integration of KPIs within a 4D BIM environment can support more structured environmental impact assessments and enable data-driven decision-making in construction planning.

4. Toward a new method to evaluate local issues across project variants using 4D BIM

4.1. Overview of the proposed Method

This section presents a method to analyze local environmental, social, and economic impacts by integrating and simulating environmental-focused KPIs into the 4D BIM models.

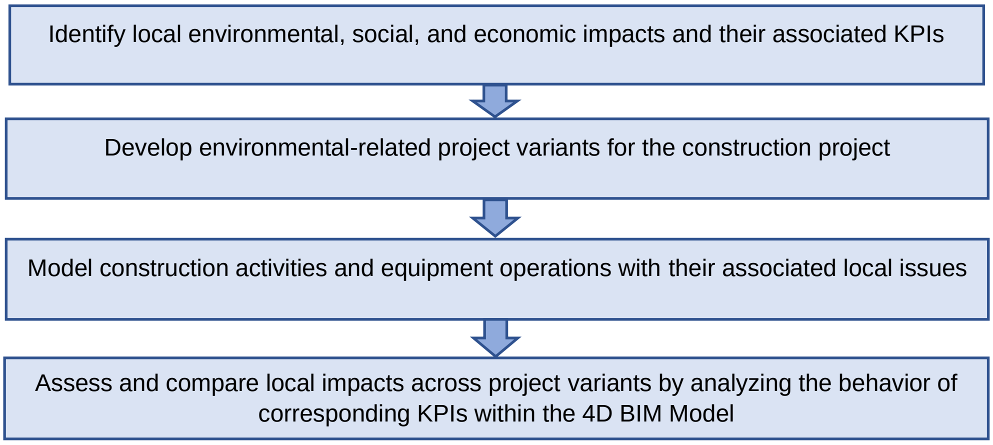


Fig. 2. The proposed method.

As Fig. 2 shows, the approach begins with the identification of local issues that commonly arise during construction activities. The purpose of this step is to ensure that the environmental, social, and economic dimensions of local impact are well understood and contextually grounded in both academic research and practical guidelines. Following the identification of key local impacts, the next step involves defining a set of measurable KPIs that represent these impacts in a quantifiable form. To evaluate the influence of various construction strategies on local impacts, a series of environmentally distinct project variants is developed. Each variant should be modelled within 4D BIM software, while construction activities and equipment operations with their environmental impacts are mapped in detail. The previously defined KPIs would be integrated into the 4D BIM model by linking each indicator to its associated construction tasks. Finally, the behaviour of these local environmental, social, and economic KPIs across all project scenarios is analyzed, enabling a detailed assessment and comparison of the variants.

4.2. Step 1: Identify local environmental, social, and economic impacts and their associated KPIs

To assess the localized consequences of construction activities, this section identifies local environmental, social, and economic impacts based on an extensive literature review and alignment with international environmental standards, including EMAS, ISO 14001, and ISO 21929-1. These sources highlight the complex and interrelated nature of environmental issues that affect both the natural ecosystem and the well-being of nearby communities. The local issues are categorized under three primary dimensions, environmental, social, and economic, to ensure comprehensive coverage and clarity in analysis, as shown in Table 1. Each identified impact is subsequently associated with a measurable KPI, enabling both qualitative and quantitative evaluation throughout the construction lifecycle.

4.3. Step 2: Develop environmental-related project variants for construction projects

Developing environmental-related project variants is a critical step in both Environmental Impact Assessment (EIA) and sustainable construction planning. This phase involves identifying and formulating alternative strategies for executing a construction project, each differing in terms of methods, materials, equipment choices, scheduling sequences, or technologies, to minimize negative impacts on the local environment. By considering multiple alternatives, decision-makers are better equipped to compare the environmental performance of each scenario and select the most sustainable option.

4.4. Step 3: Model construction activities and equipment operations with their associated local issues

By combining environmental simulation tools and 4D BIM software, each variant can be modelled along with the spatial and temporal evolution of environmental impacts. Within this digital environment, construction activities and equipment operations with their environmental impacts are mapped in detail, including their duration, location, and interaction with surrounding environments. This integration is essential for identifying key local environmental impacts, major impact sources, primary receptors, and appropriate mitigation strategies early in the planning phase, thereby enabling more environmentally friendly decision-making.

Table 1. Local environmental, social, and economic impacts and their associated KPIs.

Local environmental impacts	**KPIs**
Noise [14]	dB(A)
Vibration [14]	Vibration velocity (mm/s)
Dust [14]	Particulate matter concentration (PM10 in μg/m³)
Odor [13]	Odor detection threshold (Dilution-to-Threshold [D/T] ratio)
Excessive cut and fill [15]	Volume of earth moved (m³)
Slope failures and landslides [15]	Landslide impact area (m² or hectares)
Soil erosion [15]	Soil erosion rate/soil loss (kg/m²/day)
Irregular flood [15]	Flood occurrence frequency (incidents per project duration)
Changes in the color and smell of the runoff [15]	Pollutant concentration in runoff (mg/liter)- Frequency of odor complaints (per week)
Groundwater depletion [16]	Groundwater extraction rate (m³/day)
Spill of chemical substance [15]	Amount of chemical spilled (liters or kilograms)
Oil/fuel spills [15]	Amount of oil/fuel spilled (liters)
Open burning [15]	Emission produced (kg/day)
Loss of landscape [14]	Area of landscape altered or removed (m² or hectares)
Mine overexploitation [16]	Resource extraction intensity (kg/m²/day)
Increased temperatures in urban areas [16]	Urban heat island intensity (°C above baseline)
Deforestation [17]	Forest loss rate (m² or hectares/day)
Vegetation depletion and damage to local flora [15]	Number of trees or plant species removed
Increasing wildlife mortality [18]	Wildlife mortality rate (incidents per km²)
Destruction of animal habitat [15]	Area of habitat lost (m²) - Number of impacted species
Restricting animal movements [18]	Number of wildlife corridors affected- Length of habitat fragmentation (meters/km)
Degradation of habitat quality [18]	Habitat quality index (1-5 scale)
Disturbing gene flow & metapopulation dynamics [18]	Fragmented populations (number)- Genetic diversity index (1-5 scale)
Local economic impacts	**KPIs**
Temporary closure of local businesses [19]	Number of businesses closed
High transportation costs [20]	Cost per km increase ($/km)
Impacts on local market development [20]	Change in local business revenue ($/day)- Foot traffic in commercial areas (visitors/day or % change)
Decreases in economic growth [20]	Local Gross Domestic Product (GDP) change (%)
Increase the price of consumer goods [20]	Average price change of essential goods (% per week)
Loss of income [17]	Business revenue loss ($/day)- Number of affected workers (people)
Loss of tax revenues [17]	Decrease in local tax collection ($/quarter)
Productivity reduction [17]	Reduction in working hours per employee (hours)
Property damage and restoration costs [17]	Cost of repairs per square meter ($/m²)
Local social impacts	**KPIs**
Traffic congestion [14]	Traffic flow rate (vehicles per hour)
Diversion route effects [17]	Additional travel distance (km)
Prolonged closure of road spaces [14]	Duration of road closures (hours/ days per project duration)

Table 1. Local environmental, social, and economic impacts and their associated KPIs (continued).

Local social impacts (continued)	**KPIs**
Road safety problems [14]	Number of traffic accidents (per day or week)
Safety hazards in the area [14]	Number of reported incidents (per day or week)
Heightened wear and tear on local infrastructure [19]	Pothole frequency (per km)
Power outages or disruptions [19]	Number of power interruptions (per day or week)
Loss of peace and quietude in the neighborhood [14]	Number of complaints
Dirtiness near the entrances of sites	Cleaning frequency (times per day or week)
Landscape alteration	Visual impact rating (1-5 scale)
Limited access to educational opportunities [20]	Number of missed school days
Barriers to primary healthcare access [20]	Number of missed medical appointments
Relocating people [16]	Number of people relocated
Population growth [16]	Population growth rate (%)
Increase of crime [16]	Crime rate change (incidents per 1,000 people)
Physical/ mental health issues [17]	Number of health complaints reported (cases per day)
Reduced quality of life [14]	Community satisfaction index (survey-based, 1–5)
Archaeological harm [16]	Number of heritage sites impacted

4.5. Step 4: Assess local impacts across project scenarios by analyzing the behavior of corresponding KPIs within the 4D BIM Model

This step is crucial for enabling evidence-based decision-making that balances construction efficiency with environmental and community well-being. By evaluating how different equipment choices, construction activities, and task sequences affect KPI outcomes, such as noise levels, air quality, or traffic disruption, project planners can assess trade-offs and select the scenario that minimizes harmful impacts on the local environment. This approach transforms the 4D BIM model from a purely coordination and visualization tool into a platform that allows spatio-temporal analysis of environmental disturbances and supports what-if scenario testing, which is essential for sustainable project planning [9]. Most importantly, it provides measurable insights that can be communicated to stakeholders and regulatory bodies, enhancing transparency and accountability in the decision-making process.

5. Evaluate and validate the proposed method for assessing local impacts in project variants

This section presents the application of the proposed KPI-based framework within the 4D BIM environment to evaluate and compare the local impacts of different construction scenarios. By developing environmental-related project variants, modeling construction activities and their local issues, and linking measurable KPIs to scheduled tasks in 4D BIM, this approach enables the simulation and assessment of construction activities and equipment operation on nearby receptors.

5.1. Identify local impacts of the construction project and their associated KPIs

To demonstrate the practical implementation of the proposed framework for evaluating local environmental impacts, a construction scenario is developed. This scenario is based on a hypothetical yet realistic example involving the rehabilitation of a segment of Cavendish Boulevard in Montreal, located in front of residential buildings at 3285 and 3333 Cavendish. These buildings are six-story structures with a height of approximately 22 meters, as illustrated in Fig. 3. The scope of the rehabilitation project includes the repaving of the asphalt surface with asphalt pavers. It is a common urban infrastructure activity that causes various localized environmental disturbances, most notably noise pollution. In this case, the analysis is focused specifically on the noise impact, one of the most significant and immediate local issues, which is measured in decibels dB(A).

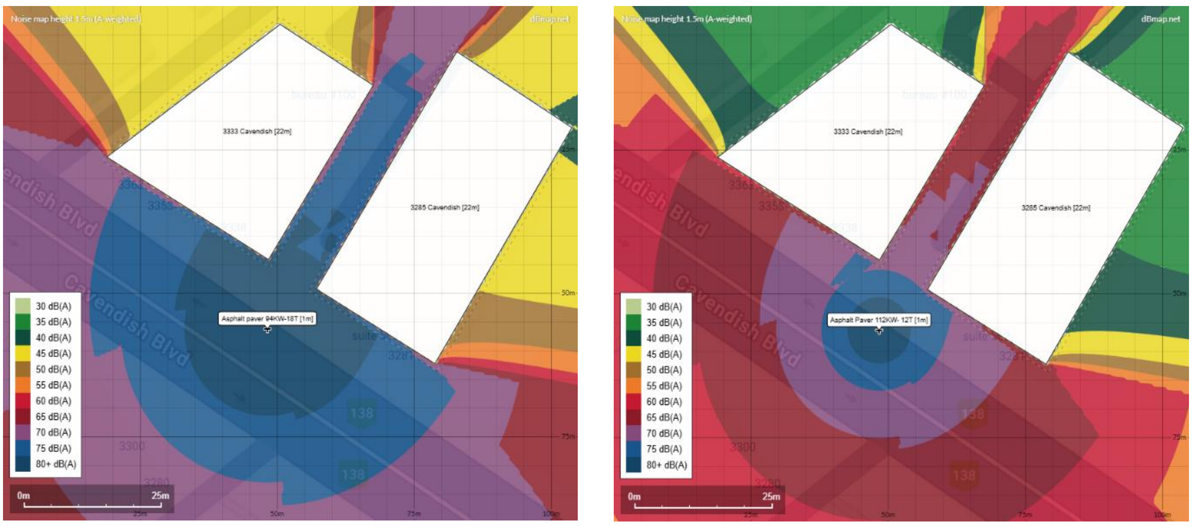
5.2. Develop project variants for the construction project

For the purpose of this analysis, two alternative equipment options are considered for the asphalt paving operation. The first variant involves the use of an asphalt paver with a 112 kW engine and a 12-ton hopper, while the second variant utilizes an asphalt paver with a 94 kW engine and an 18-ton hopper. These two pavers act as the primary sources of noise emissions during construction. Although both machines are functionally suitable for the project, they differ in terms of engine capacity, size, and operational characteristics, which directly influence the intensity and frequency of noise emitted during construction activities. In the context of environmental impact assessment, it is essential to consider not only the type and characteristics of the noise source but also the location and properties of the receptors, such as nearby buildings, green areas, or pedestrian zones, that are exposed to the noise [13]. Therefore, the severity, significance, and spatial extent of the noise impact depend on several factors, including the distance between the source and receptor, the material and height of receptor structures, the presence of barriers, and the duration of equipment operation. These parameters are critical in determining the environmental performance of each variant and must be carefully modelled and analyzed to support effective environmental management and mitigation strategies.

5.3. Model construction activities and equipment operations along with their local environmental issues

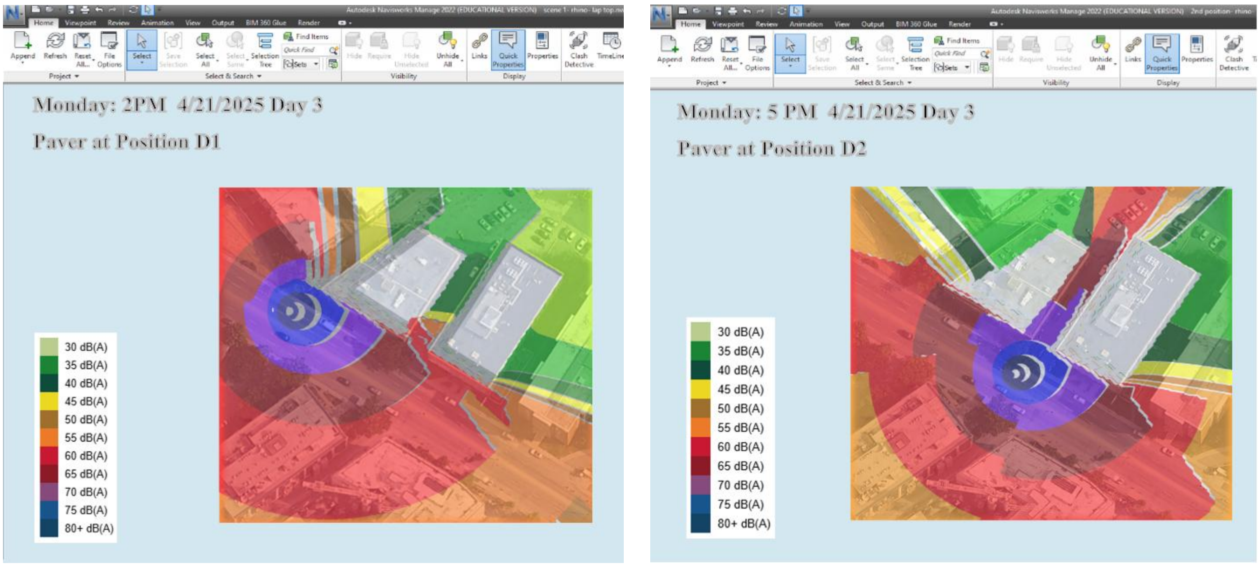
To effectively evaluate the noise pollution generated by construction activities and equipment operations, a digital model of the project is developed using a combination of noise mapping and 4D BIM tools. The aim of this step is to simulate how noise propagates from different equipment sources to nearby receptors over time, leading to a comprehensive environmental impact analysis. As a first step, the noise mapping process is carried out using dBmap, a dedicated acoustic simulation tool designed to visualize noise levels in relation to both source characteristics and receptor conditions. In this case, asphalt pavers are defined as the primary noise sources. For each variant, the main receptors are defined as the residential buildings located at 3285 and 3333 Cavendish Boulevard, which are situated directly across from the construction zone. The noise propagation maps enable visualization of the expected sound levels across the project area for each scenario.

Fig. 3(a) and 3(b) illustrate the comparative, color-coded noise dispersion of the two equipment configurations. Once the noise simulation results are generated, the outputs from dBmap are imported into Autodesk Revit, where the surrounding buildings and site conditions are geometrically modeled. This allows for the precise spatial representation of the built environment, which is essential for accurate environmental impact analysis. The completed Revit model is then imported into Navisworks, a 4D BIM coordination and simulation tool that enables the combination of construction scheduling with 3D spatial data. The next critical step involves linking the KPIs defined in Section 4 to the corresponding tasks. Navisworks allows project planners to simulate the sequence of construction activities and overlay local issues. Fig. 4(a) and 4(b) compare the noise propagation maps of the 112 kW paver under two different conditions, demonstrating how the noise distribution of a single piece of equipment can vary depending



(a) (b)

Fig. 3. (a) Noise propagation map for 94 kW -18 ton asphalt paver (Lmax); (b) Noise map for 112 kW-12 ton asphalt paver with hopper.



(a) (b)

Fig. 4. (a) Visualization of 112 kW- 12 ton paver at location D1 at 2 PM; (b) Modeling of 112 kW paver in Navisworks at location D2 at 5 PM.

on its location and time of operation. These variations may result from the presence of other impact sources and receptors at different locations and times, influencing the simulation outputs. It should be noted that the simulation process was conducted hypothetically, as modeling construction activities and equipment operation at precise times (such as minutes or seconds) in Navisworks presents certain challenges. However, 4D BIM software like Fuzor provides the capability to simulate equipment movements at a high level of detail, offering a promising alternative for conducting precise simulations in future studies.

5.4. Assess and compare local impacts across the project variants using the 4D BIM Model

In the context of this study, the comparison focuses specifically on the noise impacts of two different asphalt pavers used during a road rehabilitation project in Montreal. Both machines were modeled within the 4D BIM environment, with their respective noise propagation results linked to scheduled tasks. Analysis of the simulation results reveals that the 94 kW asphalt paver with an 18-ton hopper generates higher and more widespread noise levels, particularly along the southern facades of the nearby buildings, with several areas exceeding 75–80 dB(A). This outcome is attributed to the machine's longer operational duration and greater material throughput, which result in sustained noise exposure over a broader area and increased potential for prolonged residents and community disturbance. In contrast, the 112 kW paver with a 12-ton hopper, despite having a more powerful engine, produced a more concentrated noise field with peak levels clustered near the immediate work zone, as shown in Fig. 3 (b). While the noise intensity was high, its impact was limited to a smaller area and a shorter timeframe. This distinction highlights the importance of evaluating not only noise magnitude but also its spatial and temporal distribution. Therefore, the 112 kW paver emerges as the less disruptive alternative for locals and a more efficient option for this project. Through this analysis, planners can identify environmental risks, apply mitigation measures, and optimize construction plans before the construction phase.

6. Discussion

Local environmental issues are inherently connected to broader sustainability concerns, including economic and social dimensions. For example, noise pollution can negatively influence local economic performance by deterring pedestrian activity, reducing customer presence near commercial areas, or disrupting daily business operations. It can also cause social impacts, including psychological stress, reduced quality of life, and community dissatisfaction. In addition, noise is often accompanied by dust and particulate emissions, especially during paving, excavation, or demolition operations [13]. These issues share receptors, exacerbate each other, and should not be assessed in isolation. The use of KPIs to quantify these impacts provides a structured way to evaluate environmental performance.

However, it's important to recognize that these indicators are interconnected and effective impact assessment requires an integrated, multi-dimensional analysis of these relationships.

Using 4D BIM allows planners to simulate and analyze the evolution of environmental impacts across different project scenarios. The 4D-based analysis approach is crucial for the early identification of high-impact construction activities and equipment, enabling mitigation planning before the construction phase. For example, by linking equipment noise data to scheduled paving activities, project teams can visualize when and where sensitive receptors will be most affected, and accordingly reschedule or shield operations during vulnerable hours. However, 4D BIM tools do not natively generate environmental impact data such as noise, dust, or traffic congestion. To achieve this, external environmental-specific tools, such as dBmap or SoundPLAN for noise mapping, or other simulation software for air quality, energy use, or traffic congestion, should be used. The outputs of these tools should then be integrated with the BIM model, often requiring manual data handling or custom interoperability workflows. This can be time-consuming, particularly when simulating multiple activities and their dynamic impacts over time. In addition, the interoperability limitations between some simulation platforms and BIM software can be a barrier to the broader adoption of such methods.

It should be noted that the proposed model represents a simplified scenario with only two primary receptors. In reality, construction projects in urban areas include several environmental impact sources and a more complex network of noise-sensitive receivers, including schools, parks, and healthcare facilities. Nevertheless, this approach highlights the potential of 4D BIM to support environmentally informed construction planning by embedding environmental KPIs and visualizing their evolution throughout the project timeline, thereby empowering stakeholders to make sustainability-oriented decisions while minimizing disruptions to local communities. Equally important is the comparison of construction variants, which enables planners to select solutions that not only meet technical requirements but also address environmental, economic, and social challenges.

7. Conclusion

This study presents a KPI-based approach for assessing local environmental, social, and economic impacts within a 4D BIM environment, enabling the visualization, simulation, and analysis of various environmentally oriented project variants. This approach enables dynamic tracking of localized impacts over time by identifying measurable indicators for local issues. The defined indicators, grounded in literature and environmental standards, enable targeted analysis of local issues, which are often overlooked in traditional environmental assessments. The simulation of environmentally distinct project scenarios further demonstrates how data-driven modeling can enhance proactive decision-making, foster transparency, and support the development of more sustainable construction strategies.

The implementation of this approach on a simplified paving scenario illustrates the practical value of the integration of environmental simulations with 4D BIM tools. The comparison of equipment alternatives revealed significant differences in noise propagation and exposure duration at nearby receptors, emphasizing the importance of early impact assessment and variant analysis. This also highlights the importance of early decision-making grounded in data, where even minor differences in methods or machinery can have meaningful impacts on nearby communities. Moving forward, future research should focus on simulating a wider range of local issues within 4D BIM models, such as dust, odor, and traffic congestion, while also exploring the interconnections among environmental, social, and economic impacts to support more integrated and informed decision-making.

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