4D-Based Environmental Impact Analysis of Road Project Variants

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Road construction work has a multitude of impacts on its host environment, and the effect of these impacts varies according to the areas it crosses. Taking these impacts into account from the earliest stages of project planning is the ideal approach pursued by planners to ensure that their plans not only take these impacts into account but also mitigate their effects as much as possible. Drawing up a project schedule that considers the impact of the work requires an in-depth understanding of its scale, spatial extent, and timing.

road construction | environmental impact assessment | 4D construction simulation

1. Introduction

The construction industry is responsible for 36% of global final energy consumption, 39% of carbon dioxide (CO_2) emissions linked to energy and construction processes, 10% of suspended particulate emissions, and 25% of waste [1]. The environmental impact of the construction process is generally expressed by the supply of materials, the consumption of 20–50% of natural resources, and the overall impacts on the surrounding environment and local residents [2]. Taking these impacts into account from the earliest stages of project planning is the ideal approach pursued by planners to ensure that their plans not only take these impacts into account but also mitigate their effects as much as possible.

In road projects, the effects of these impacts on the sensitive elements of the receiving environment and on public health, convenience, and safety are difficult to determine due to the linear nature of these projects [3]. Unlike buildings, road projects are large and elongated and may cross different areas with different functions, such as residential areas, natural parks, or lakes. The project team must consider the various issues surrounding the zone of influence (the road right-of-way and the borrow sites) of the planned road when determining the impact of the work. However, the difficulty of understanding the spatial extent and timing of these impacts poses a problem for mitigation planning due to the complex and variable nature of the impacts [4]. Poor planning of construction impacts can result in significant non-compliance, delays in project planning, and sometimes the environmental and social non-acceptability of the project [5].

Over the last three decades, several environmental assessment tools have been developed to better manage the impact of the construction industry on the environment, including the Environmental Impact Assessment (EIA). EIA is presented as an original environmental assessment tool that provides a technical response to biophysical and social impacts while focusing on health, socio-economic issues, and public policies [6]. EIA is a systemic process with its own administrative and technical procedures. The idea of integrating environmental issues from the very first phase of project planning has been unanimously endorsed by decision-makers and implementation professionals alike. The analysis of project variants appears to be an approach that makes it possible to evaluate the different possibilities for carrying out the work and to unite the various stakeholders around an optimal variant. However, the literature has shown that the traditional method of analyzing variants of construction projects does not resolve the difficulty of understanding the spatio-temporal nature of the impacts of linear facilities on the environment [4].

Furthermore, the last decade has seen the automation and digitization of construction sites, which have become drivers of productivity in the construction sector [7]. Today, digital mock-ups and the collaborative digital approach are positioned as technological tools for creating, sharing, and managing information on structures/products throughout the project lifecycle [8]. This working method is known as BIM (Building Information Modeling). BIM 4D is a level of BIM development that combines the temporal dimension with a 3D digital model of the structure to be built so as to simulate its construction through time [9][10]. These tools are gradually proving indispensable for design and planning in the construction industry. It is therefore legitimate to question their implementation for the environmental analysis of road projects at the initial decision-making phase.

In the literature, numerous works have shown progress in the use of BIM to define and estimate the public and environmental impacts of road projects [11][12][13]. However, little research [4][14] has addressed the issue of using the BIM approach to support planning for the environmental impacts of road projects from the earliest decision-making phase, i.e., the links and influences between the design of the structure and the requirements for selecting an optimal project variant. Indeed, design decisions regarding site selection, optimal project size, type of facility, technology, and process have a significant impact on the public, sensitive elements of the project's host environment, and even the ability of workers to perform their various tasks [15]. It therefore makes sense to assess the possibilities of deploying BIM 4D to support the process of analyzing and selecting variants for road projects. Indeed, the use of 4D simulation could provide a highly valuable visual aid to visually characterize and compare different design variants. It could also simulate various aspects of a variant, including the time evolution of the impact of construction operations. This can serve as a decision support tool, enabling planners and professionals to make informed choices. It also allows other project stakeholders, who may not always be construction specialists, to better understand the project and contribute more effectively to its definition and social acceptance. However, there is currently no theoretical framework in the scientific literature for using 4D simulation to support variant analysis in road construction projects.

2. Environmental Impact Assessment in the Construction Industry

To understand the term "environmental impact assessment", we need to analyze the three distinct concepts of assessment, impact, and environment that represent EIA. The concept of "assessment" in the context of EIA is a forward-looking, operational practice involving divergent points of view on a given issue. It is a process that involves discussion, talks, and negotiations. The term "impact" defines the orientation of the assessment to be carried out. It indicates the magnitude, extent, and duration of the consequences measured for the environmental element. Finally, the concept of “environment” delimits the impacts to be considered in the assessment, even though there is no unanimity on its definition and it does not always encompass the same realities. Nevertheless, for some time now, in the context of EIA, the environment has referred to all the elements surrounding a living being, a population, or a community, as well as the natural and artificial factors that affect them [16].

Based on the three concepts defined above, the term “environmental impact assessment” can be defined as a systemic process for examining and negotiating all the consequences of a project on the natural and human elements of its insertion environment. The United Nations Environment Program (UNEP) defines EIA as “a tool for identifying the environmental impacts of a construction project at the decision-making stage and prior to statutory approval” [17].

In the construction industry, EIA can be defined as a two-way process: (1) assessing the impact of construction on the environment and proposing mitigation measures; and (2) analyzing the evolution of environmental aspects, such as the climate, in relation to the installation.

EIA practices in the construction industry draw on many environmental aspects to better plan the environmental quality of construction. The literature shows that there is no clear consensus regarding the classification of the environmental impacts of construction, which vary in terms of products and construction processes [18]. Nevertheless, the widely recognized Eco-Management and Audit Scheme (EMAS) identifies the following environmental aspects: air emissions; water discharges; solid and other wastes; land use and contamination; use of natural resources and raw materials; local problems (noise, vibration, odors, dust); transport problems; accidents and potential emergency situations; and effects on biodiversity [19]. The ISO 14001:2015 standard [20] and the national standards of the various countries, generally referred to in the environmental management plan report, provide structure and guidance for the environmental analysis processes of construction projects.

The EIA process begins with the initial information phase and continues as a collaborative effort through the project validation phase [21]. The process thus depends on the contribution of different disciplines such as basic sciences (biology, chemistry, etc.) and applied sciences (engineering and management). It should also be noted that the EIA process follows an administrative procedure based on the regulations and institutions governing impact assessment in each country.

3. Analysis of Variants

Linear projects (roads, railroads, etc.) spread over large areas of land or regions, crossing various natural and urban environments, can generate significant negative impacts. These projects must undergo a strategic environmental assessment, including variant analysis. The analysis of variants is a preliminary step occurring before the planning of the Environmental Impact Assessment (EIA). It entails the assessment of various potential methods for executing the project, as indicated in reference [5]. This process of variant analysis entails a comparison of the pros and cons of each option and aims to pinpoint the option that optimally aligns with a range of criteria, including technical, economic, and environmental aspects [22]. At the variant analysis stage, alternative sites, designs, and timetables for the various project components are evaluated, leading to the selection of an optimal variant. The national guide to environmental impact assessment in France divides the variant analysis process into three main stages [22]: the analysis of the likely evolution of the environment in the absence of project implementation, the generation and analysis of each project variant, and the comparison of variants.

Regarding the first stage, it involves analyzing the likely evolution of the physical environment (hydrology, relief, and soil), the likely evolution of the natural environment (land use, crops, meadows, and woodlands), the likely evolution of the human environment (agriculture, urbanization, acoustics, and other projects), and the likely evolution of the landscape and heritage.

The actual analysis of variants is generally carried out as follows:

- Identification of objectives: this stage involves clearly defining the project's objectives. The identification of objectives helps guide the variant analysis process.

- Variant generation: in this step, different options or variants for the project are generated. This may include variants in terms of route, design, sizing, materials, technologies, etc. The aim is to explore a wide range of possibilities to meet the identified objectives.

- Evaluation criteria: evaluation criteria are defined according to the project objectives. These criteria may include environmental, social, economic, technical, and operational considerations. For example, criteria may include impacts on ecosystems, local connectivity, construction costs, timescales, safety, etc.

- Variant analysis: each variant is evaluated quantitatively and qualitatively according to defined criteria. This may involve the use of models and analysis tools, such as 3D models of the structure, environmental impact assessments, cost-benefit analyses, risk analyses, and so on. The results of this analysis enable us to compare the performance of each variant.

The comparison of variants involves:

- the selection of the best variant: based on the results of the analysis, the best variant is selected, considering relative performance against objectives and criteria. This step may involve weighting the criteria according to their respective importance. The variant selected is the one that offers the best balance between the various criteria.

- validation and decision-making: the selected variant is then validated and refined, if necessary, according to technical, regulatory, budgetary, and feasibility constraints. Once the variant is considered viable, a final decision is taken to implement the project.

- It should be noted that the specific stages and details of variant analysis may vary according to the project and context.

It should also be noted that understanding each environmental impact, its potential impact, and its significance in relation to construction activities is a complex and challenging process.

4. Environmental Planning Challenges in the Construction Industry

In the construction industry, as in other sectors, the challenges of the environmental analysis process are generally related to process and information for stakeholders. Julie Jupp's work [14] has identified six main challenges related to the environmental planning and management process. These challenges can be applied to the variant analysis process:

- Communication gaps and poor information flow: Compartmentalized practices in the EIA process result in poor information flows between project participants and inconsistencies in information transfer, storage, accessibility, and redundancy. Environmental planning is a complex process involving several actors, such as the multilateral development banks, the government concerned, the consulting firm (with a range of expertise in multiple disciplines), and the project host community. The constraints associated with gaps in communication and poor information flow are mentioned by Tam et al. as the two main challenges in the environmental planning and management process [23].

- Delineating the project's zones of influence: Construction projects generally generate environmental impacts over a relatively short period, but with a high density of potential impacts on many aspects of the environment [24]. These impacts can be divided into two zones of influence: the project's direct zone of influence, where the installation site is located and varies from 0–5 km in radius, and the indirect zone of influence, which encompasses borrow sites, supply routes, etc. [25]. The scope of environmental impacts is often very wide, which makes it difficult to assess project impacts on a human scale.

- Using the traditional 2D paper approach: 2D representations are presented as obstacles to improving the environmental analysis process. The literature has shown that they are inadequate to facilitate the identification of environmental impacts associated with construction activities, including an understanding of the nature of the structure and associated workspaces and of the site. In addition, mitigation and control measures depicted in 2D may overlook or minimize environmental risks [14]. Strategies for controlling and managing environmental impacts are generally drawn using different colors on the drawings. However, these drawings do not show the link between environmental controls and the construction schedule.

- Interdependencies between environmental control and management plans: Identifying and planning the impacts of construction on the various environmental aspects in a well-developed plan is a major challenge. This challenge is due to the usual changes in construction schedules (weather conditions, delays in the delivery of materials). The dynamic nature of construction projects can distort the planning of mitigation measures, which can lead to changes in the control plans for identified impacts. It is also difficult to identify certain impacts, for example, those that will be caused by contaminated construction waste. On-site communication using paper plans of environmental impact interdependencies may therefore not be managed appropriately [26].

- Methods for assessing the significance of environmental impacts: Impact assessment criteria (scale, severity, impact duration, type, size, and frequency), applicable legal requirements (emission and discharge limits in regulations), and the concerns of internal and external stakeholders are elements to consider when specifying the environmental analysis method for construction projects [27]. Liu et al. mention that some designed EIA methods are not conducive as a pre-construction assessment tool to support the decision but rather as a tool that aims to facilitate the acceptance of predefined works [28]. It should also be noted that some methods are based on qualitative and subjective scores, making them difficult to interpret and integrate into project planning.

5. Use of 4D Simulation for Environmental Impact Analysis

4D simulation combines the schedule with the 3D digital model of the structure so as to simulate its construction over time [9]. It is an approach that provides a 3D model for each selected unit of time, i.e., a view of the possible state of construction at each selected moment [29]. 4D simulation techniques can therefore facilitate the integration of spatial data visualization with construction planning information in 3D models and enable efficient visualization of the spatial and temporal attributes of different impacts.

The literature has shown that the functionalities of BIM 4D can be divided into two parts: (i) construction planning and (ii) site planning. BIM 4D applications for construction planning include work allocation at the tender stage, construction method planning, schedule communication, conceptual analysis, resource management, workspace planning, risk identification, and safety planning [30]. 4D applications for site planning consider site logistics, pedestrian and traffic flows, material delivery and storage, major plant activities, temporary works, welfare facilities, and site safety. Jupp's recent work has identified five functional prerequisites for the use of 4D in environmental assessment: (i) scheduling and simulation; (ii) environmental equipment modeling; (iii) site layout modeling; (iv) environmental impact significance modeling and visualization; and (v) rule verification capability [14]. Despite several algorithmic methods used to define and estimate the environmental impacts of roadworks [31], the issue of supporting spatio-temporal environmental performance indicators remains.

However, the work of Zanen et al. on the use of 4D BIM to visualize the public impacts of highway construction comes closest to the present research question [4]. Despite the limitations encountered in their work, analysis of the results of practitioner surveys showed that the 4D modeling method offers practitioners an easier tool for visualizing and assessing impacts on the public than traditional methods based on 2D construction stage drawings. The objective of the research is to contribute to the improvement of the EIA process by proposing a structured framework for the deployment of 4D simulation to support the process of variant analysis for a road project. The specific objectives can be formulated as follows:

- Characterize environmental impact assessment practices in the construction industry;

- Develop a conceptual framework for the use of 4D technologies to support the variant analysis process;
- Develop a proof of concept through case studies.

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