Sustainability through the use of Building Information Modelling in infrastructure planning

Sustentabilidade por meio do uso do Building Information Modelling no planejamento de infraestrutura

Sostenibilidad mediante el uso de modelos de información de construcción en la planificación de infraestructuras

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Abstract
This study examines the role of Building Information Modelling (BIM) in infrastructure planning from a sustainability perspective. It emphasises how BIM can contribute to the promotion of ecological, economic and social sustainability. Interviews with experts have shown that BIM can not only optimise the energy consumption of infrastructure projects, but also lead to precise material quantification and optimisation. Despite the benefits, the use of BIM in infrastructure planning is limited, especially in small and medium-sized projects and with local authorities. The study identifies challenges such as the complexity of BIM software systems and the additional costs of implementing them. Recommendations for action include training clients and engineering firms in the use of BIM for cost forecasting and extending the digital twin concept beyond the construction and planning process. The results show that widespread BIM application is only possible if both clients and planning offices share sustainability goals and are prepared to bear the additional costs for BIM planning. The work emphasises the need to use BIM beyond building construction for sustainable infrastructure development and provides insights into the practice of engineering firms in the infrastructure sector.

Keywords: Building Information Modelling. Sustainable Infrastructure. Resource Efficiency. Implementation.

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Resumo
Este estudo examina o papel do Building Information Modelling (BIM) no planejamento de infraestrutura a partir de uma perspectiva de sustentabilidade. Ele enfatiza como o BIM pode contribuir para a promoção da sustentabilidade ecológica, econômica e social. Entrevistas com especialistas mostraram que o BIM pode não apenas otimizar o consumo de energia de projetos de infraestrutura, mas também levar à quantificação e otimização precisas de materiais. Apesar dos benefícios, o uso do BIM no planejamento de infraestrutura é limitado, especialmente em projetos de pequeno e médio porte e com autoridades locais. O estudo identifica desafios como a complexidade dos sistemas de software BIM e os custos adicionais de sua implementação. As recomendações de ação incluem o treinamento de clientes e empresas de engenharia no uso do BIM para a previsão de custos e a extensão do conceito de gêmeo digital para além do processo de construção e planejamento. Os resultados mostram que a aplicação generalizada do BIM só é possível se tanto os clientes quanto os escritórios de planejamento compartilharem as metas de sustentabilidade e estiverem preparados para arcar com os custos adicionais do planejamento do BIM. O trabalho enfatiza a necessidade de usar o BIM além da construção de edifícios para o desenvolvimento de infraestrutura sustentável e fornece insights sobre a prática de empresas de engenharia no setor de infraestrutura.


Resumen
Este estudio examina el papel del Building Information Modelling (BIM) en la planificación de infraestructuras desde la perspectiva de la sostenibilidad. Destaca cómo el BIM puede contribuir al fomento de la sostenibilidad ecológica, económica y social. Las entrevistas con expertos demuestran que el BIM no sólo puede optimizar el consumo energético de los proyectos de infraestructuras, sino que también permite cuantificar y optimizar con precisión los materiales. A pesar de sus ventajas, el uso del BIM en la planificación de infraestructuras es limitado, especialmente en proyectos pequeños y medianos y con las autoridades locales. El estudio señala retos como la complejidad de los sistemas de software BIM y los costos adicionales de su implantación. Las recomendaciones de actuación incluyen la formación de clientes y empresas de ingeniería en el uso de BIM para la previsión de costes y la extensión del concepto de gemelo digital más allá del proceso de construcción y planificación. Los
resultados muestran que la aplicación generalizada del BIM sólo es posible si tanto los clientes como las oficinas de planificación comparten los objetivos de sostenibilidad y están dispuestos a asumir los costes adicionales de la planificación BIM. El trabajo subraya la necesidad de utilizar el BIM más allá de la construcción de edificios para el desarrollo sostenible de infraestructuras y aporta ideas sobre la práctica de las empresas de ingeniería en el sector de las infraestructuras.

**Palabras clave:** Building Information Modelling. Infraestructuras Sostenibles. Eficiencia de los Recursos. Implantación.

**Introduction**

The use of Building Information Modelling (BIM) methodology has played a transformative role in the architecture, engineering and construction industry over the last few decades, with its influence increasing significantly, particularly in the field of structural engineering. The methodology enables a highly accurate, digital representation of structural designs that encompasses all physical and functional features of a project, providing a basis for decision-making throughout the lifecycle of the structure, from initial conception to demolition (Borrmann et al., 2018). Despite its widespread use in building construction, there are clear differences in the adoption of the BIM method in the planning of infrastructure measures. While many European countries already use the BIM method extensively in most building construction projects, its use in infrastructure planning remains predominantly limited to large-scale projects. These are often supported by national initiatives and funding, such as in Germany by the federal government. In contrast, the BIM method is used less frequently in the planning of smaller infrastructure projects. Local authorities and municipalities do not necessarily specify the use of BIM for such measures, which means that engineering firms specialising in traffic, sewer and route planning continue to rely on traditional planning methods (Charef et al., 2019).

The reluctance to implement the BIM method across the board in infrastructure planning is partly due to the complexity of the software systems required. These often do not offer the necessary interfaces for efficient utilisation in the specific context of the infrastructure. In addition, the costs associated with the introduction of BIM - for example for additional software licences, employee training and the conversion of internal work processes
lead to a further inhibition threshold for many engineering firms. These are particularly difficult to justify if clients do not explicitly require the use of the BIM method. Nevertheless, the implementation of BIM offers significant advantages. Once fully established, BIM can contribute to a considerable reduction in planning errors and significantly improve communication between all project participants (Eadie et al., 2013). The possibility of three-dimensional modelling and visualisation also makes it easier for non-experts to understand complex construction projects. Beyond these practical benefits, BIM plays a crucial role in promoting sustainability in infrastructure projects. This is particularly relevant as such projects are often of public interest and have a long-term impact on the environment and society (Wong et al., 2015).

Despite the obvious benefits and potentials of the BIM method in infrastructure planning, there is a noticeable research gap regarding its optimisation and application to increase sustainability. This thesis aims to analyse the current influence of the BIM method on the planning of infrastructure measures. In particular, the possibilities for further increasing sustainability through the use of BIM are to be worked out and the current challenges that stand in the way of widespread application are to be identified. Based on these findings, recommendations for action will be derived that can help to increase sustainability through the use of the BIM method in infrastructure planning.

**Theoretical Framework**

The research landscape on Building Information Modelling (BIM) methodology is experiencing continuous growth, with a significant proportion of the work highlighting the added value of BIM. However, it should be noted that much of this research is primarily focussed on building construction. Although there are studies on sustainability through BIM in the context of infrastructure measures, most of these works focus on sustainable urban planning, while smaller infrastructure projects in cities and municipalities are less considered.

Bonenberg and Wei (Bonenberg & Wei, 2015) argue that BIM plays an indispensable role in the planning and implementation of eco-cities and green buildings by enabling decision makers to more effectively understand and minimise the environmental impact of their projects. Dall’O’ et al. (Dall’O et al., 2020) introduce the concept of City Information Modelling (CIM) and discuss its importance in promoting sustainability at the city level. They emphasise that CIM provides an integrative platform for the planning and management of
urban infrastructure, buildings and services that supports sustainable urban development.

Razkenari et al (Razkenari et al., 2016) discuss the diverse applications of BIM in the field of sustainable building design. Through a systematic literature review, they identify key areas where BIM has the potential to optimise the design, construction and operation of buildings in terms of energy efficiency, daylight simulation and carbon emission assessment. Hewavitharana and Perera (2018) consider how the integration of Enterprise Resource Planning (ERP) systems with BIM can increase the sustainability of construction projects through improved resource planning and control, resulting in more efficient project delivery and a reduction in environmental impacts.

Santos et al. (2019) analyse the research trend regarding BIM and sustainability and note a growing interest in the integration of sustainability aspects in BIM. While some studies highlight the potential of BIM over the entire life cycle of a building (Wong & Fan, 2022) others identify challenges that stand in the way of integrating BIM into sustainable building practices (Onososen & Musonda, 2022), albeit without a specific focus on infrastructure measures.

Other studies focus on sustainability plugins or tools for BIM that can be implemented in software systems to promote the sustainable performance of BIM projects (Liu et al., 2018; Chong et al. 2017). Mészároš et al. (2021) propose a database structure for building elements that includes environmental, cost and time parameters to improve the sustainable performance of construction projects. This emphasises the need to explore and further research the potential of BIM not only in building construction, but also in the planning and implementation of infrastructure measures.

Methodology

In this study, expert opinions and specialist knowledge were collected using guided interviews and then analysed using a qualitative content analysis to structure the content. Expert interviews are regarded as an important source of information on current developments, particularly when there is a lack of existing literature. The use of expert interviews is especially recommended for the investigation of specialised sub-areas that cannot be comprehensively covered by other methodological approaches (Bogner, 2014; Kaiser, 2014). The social representativeness of the experts interviewed is defined by the specific research project and the research context (Glaser & Strauss, 1998).
When selecting the interview partners, the focus was on their expertise in infrastructure planning, with particular consideration of the BIM method. To ensure the comparability of the interviews, the experts in the field of infrastructure were limited, with a special focus on transport infrastructure and water supply and disposal. In order to collect and compare a variety of perspectives, experts from different hierarchical levels in engineering offices (managers, project managers, project engineers) and experts from cooperating companies were interviewed. Experts from consulting firms specialising in the implementation of the BIM method and training, as well as software manufacturers in the field of infrastructure planning and BIM, were also consulted. Furthermore, when selecting the experts, a particular focus was placed on German-speaking countries in order to ensure uniformity with regard to the legal situation, guidelines and standards. Data was collected until theoretical saturation was reached, at which point no additional significant data, differences or similarities could be identified (Glaser & Strauss, 1998; Misoch, 2015). A total of 19 interviews were conducted.

The interview guide consisted of open-ended main questions, which primarily served as conversation prompts. These main questions were supplemented by specific follow-up questions in order to achieve greater depth in the various subject areas (Boger, 2014).

The transcribed interviews were analysed using the content-structuring qualitative content analysis method according to Kuckartz. The interviews were structured through multi-level categorisation and coding, which enabled a transparent, category-based analysis of the various aspects. This led to a descriptive presentation of the results, followed by a critical analysis (Kuckartz, 2022). The categorisation and coding focused on the three pillars of sustainability [Fig. 1]. In addition, sub-categories were developed in order to shed light on the intersections between the pillars in detail.
Various methods of analysis from the repertoire of qualitative content analysis were used. The analysis was based on both qualitative summaries and quantitative methods such as frequency analysis. It should be noted that the quantitative results cannot be regarded as generalisable or representative per se, but are only valid for the cases examined in this study (Kuckartz, 2022).

Results

In order to analyse the influence of the BIM method in infrastructure planning on sustainability in depth, the results were divided into the three main topics of the three pillars of sustainability in accordance with the methodology. The results are described below.

4.1 The role of BIM in Promoting Environmental Sustainability in Infrastructure Projects

Experts explain that Building Information Modelling (BIM) opens up new opportunities to carry out variant analyses on an extended level. While traditional planning already takes costs and environmental factors into account when selecting variants in the planning phase, BIM also makes it possible to analyse the energy consumption of individual options. By enriching components in the 3D model not only with information on costs and time, but also with data on energy consumption, an additional basis for decision-making is
created for the client. This can lead to new insights into the overall costs, as energy consumption is playing an increasingly important role for construction companies and offers are being adjusted in line with the development of energy prices. One expert makes it clear that energy consumption not only influences costs during the construction phase, but is also relevant for the entire life cycle of an infrastructure project and should therefore be taken into consideration at an early stage. The precise prediction of energy requirements, which is optimised by BIM in infrastructure planning, makes it possible to take measures to reduce overall energy consumption in good time. This means, for example, that subsidence in the foundation or potholes in the asphalt can be recognised and rectified at an early stage during the life cycle phase in order to avoid major replacements. The same applies to ruts in the asphalt, which can occur in certain road sections with heavy goods traffic. BIM also makes it possible to take such specific information into account. One expert explains that traditional planning also takes the traffic load into account and determines the appropriate construction method based on this. However, the advantage of BIM is that the exact energy consumption during asphalt production can be determined and measures can be initiated to optimise this process in order to adapt the production time to the paving location. However, it is pointed out that the potential in this area is not being fully utilised due to the limited demand and interest from clients to date.

Another aspect frequently mentioned by the experts is the simulation of the drainage of development areas or transport facilities using BIM. This makes it possible to check more precisely to what extent the rainwater can be optimally infiltrated, which relieves the burden on the sewerage system and returns the rainwater to the natural water cycle.

The BIM method in infrastructure planning makes it possible to precisely quantify the materials required, thereby avoiding surpluses and optimising the use of materials. This leads to a significant reduction in costs and minimises the environmental impact. Experts emphasise that by using BIM in the planning phase, design errors that lead to material waste can be minimised. BIM also promotes the planning of recycling and reuse strategies for building materials. A cost comparison can be presented to the client as early as the pre-planning phase, enabling a direct comparison between recycled materials and conventional construction materials such as gravel. In addition, the exact materials can be presented to the client virtually so that an informed decision can be made before the start of construction is subject to short-term changes.
4.2 The Importance of BIM for Economic Sustainability in Infrastructure Projects

The experts describe how BIM can be used to create detailed cost forecasts in infrastructure planning. The prerequisite for this, however, is that the appropriate foundations are in place. The surrounding area must be surveyed precisely so that the existing infrastructure can be accurately recorded. This is the only way to provide exact quantities with regard to dismantling and installation, which then enables precise cost estimates to be made with BIM in the early planning phases. The experts describe that the demand from clients for BIM is currently not high, especially for small and medium-sized infrastructure measures, which is why the potential that BIM offers in terms of costs is not being fully utilised, particularly in cities and municipalities. By modelling the entire life cycle of a project, BIM can be used to take into account all costs incurred, from the initial investment to the demolition costs. For cities and municipalities in Germany, this would mean that the budget for construction projects could be planned years in advance and additional costs or savings could be announced in good time. The experts particularly emphasise that the central data management and accessibility of planning data can make construction processes more efficient and save time and costs. For the engineering firms themselves, this means that efficiency in the office can be increased and thus added value can be achieved. Experts also confirm that planning adjustments are less likely to be made as a result of planning errors or misunderstandings, as BIM promotes cooperation between all project participants, reduces misunderstandings and avoids costly errors and rework. The reason for this is that the exchange with the BIM method is continuous. Everyone involved in the project works in one system and changes are identified and can be tracked by everyone involved in the project. The BIM model created creates a kind of digital twin that facilitates future adjustments or extensions to the infrastructure and thus increases the value of the project. In addition, the detailed visualisation and analysis allows potential risks to be identified at an early stage and measures to mitigate them to be introduced. For example, hazards can be identified in good time or safety distances to important supply lines can be defined, which can be checked more precisely along the entire line. Particularly in residential areas or in development areas, it is often the case that there are a particularly large number of existing pipes in the street, and if an additional pipe is then to be integrated into the existing pipeline, collisions can occur at many points that cannot be recognised directly using the traditional planning method. For
engineering firms, this can mean additional planning work and additional costs, while the client also incurs costs in this way.

4.3 The Influence of BIM on social sustainability Aspects in Infrastructure Projects

BIM can be used to simulate environmental conditions such as light and noise in order to optimise comfort and regulate the environmental impact. One expert reports that the use of BIM in the construction of new rural roads or motorways allows modelling to be carried out in such a way that light and noise conditions can be taken into account. The road can be planned in such a way that, for example, shaded areas can be optimally utilised or measures can be arranged on the traffic areas to promote noise protection. BIM can be used to optimise accessibility during and after construction. In particularly narrow areas, for example, the areas required for construction machinery or materials can be stored in order to check whether the remaining areas are sufficient for employees. Checking this digitally in a BIM model leads to greater safety on the construction site for employees. In addition, in particularly narrow lanes or walkways, the distances can be checked more precisely and via virtual reality, and accessibility for people with physical disabilities can be checked. In traditional planning, predetermined distances from guidelines are often used at this point. One expert describes that in Germany, for example, there is a minimum width of 1.50 metres for the pavement. However, if there are other obstacles on the pavement, such as traffic lights, a light fitting, an electricity box or a simple advertising board, which were not taken into account in traditional 2D planning, this leads to a narrow section and does not comply with accessibility requirements. With the help of BIM, such defects can be recognised and eliminated more efficiently.

A significant added value for many project participants is that BIM plans can be used in public presentations to make plans understandable and to obtain feedback from the community. The experts describe that they often involve clients and local residents in the planning process at an early stage when planning transport facilities and show them the models at an early stage, as 3D modelling provides an early understanding of the project and also leads to greater acceptance among the public.
Discussions

This discussion complements the existing research literature by analysing the influence of the BIM method on sustainability in infrastructure projects, with a particular focus on practice in engineering firms in the infrastructure sector. The findings from the expert interviews conducted make it clear that BIM has the potential to support and promote all three pillars of sustainability - environmental, economic and social. Liu et al. (2018) achieve similar results in their study, but in contrast to this work, they focus more on the development of a conceptual framework for the integration of BIM and sustainability assessment systems. Kresnanto et al. (2023) dedicate their study to analysing the implementation intentions of the BIM method and in particular highlight the advantages and obstacles in relation to sustainability, but focus primarily on building construction. Sun et al. (2015) also concentrate mainly on building construction in their research and shed less light on the infrastructure sector.

Various recommendations for action were derived from the results of the expert interviews. For example, given the importance of energy consumption not only during the construction phase, but throughout the entire life cycle of a project, planners should utilise the possibilities of BIM to incorporate energy efficiency into the design from the outset. This can be done by enriching 3D models with specific energy consumption data to enable more sustainable decisions.

Accurate simulation of drainage can also have a significant impact on reducing environmental impact and promoting the natural water cycle. Engineering firms should therefore actively use BIM for such simulations and incorporate their results into the planning and decision-making process.

To fully realise the benefits of BIM in terms of accurate cost planning, it is crucial that both clients and engineering firms are trained in the use and interpretation of BIM-based cost predictions. This can help to increase awareness and demand for BIM in small and medium sized projects. The use of the digital twin created by BIM models should be extended beyond the design and construction process to the maintenance and operation of infrastructure. This can enable long-term savings and more efficient use of resources. Engineering firms should utilise BIM to consider accessibility and safety aspects at all stages of the construction process. By using virtual reality in combination with BIM, planning can be checked for bottlenecks and obstacles and optimised to ensure accessibility and safety for all users. The
use of BIM models in public presentations offers an excellent opportunity to make complex plans understandable and to obtain feedback from the community at an early stage. This not only promotes the acceptance of projects, but also enables participatory planning that takes into account the needs and wishes of local residents.

BIM is not explicitly required by engineering firms, especially in cities and municipalities, which means that engineering firms generally do not want to incur the additional costs for software systems or training and therefore do not use the BIM method. As a result, engineering firms generally only offer what clients require. BIM leads to many added values in infrastructure planning, but many municipalities still demand traditional 2D planning and do not accept BIM models, which leads to additional work for engineering firms. The BIM method can therefore only be applied across the board if clients and engineering firms pursue the same sustainability goals and accept the use of the BIM method and also remunerate the additional costs for the planning. In this way, a significant contribution to sustainability can be made.

**Conclusion**

This work represents a relevant addition to the existing literature by specifically highlighting the applicability and benefits of BIM in infrastructure design. In contrast to existing studies that primarily address building construction, this study provides insights into the specific challenges and opportunities that BIM offers for infrastructure projects. In particular, the possibilities for optimizing planning and construction processes from a sustainability perspective become clear. By focusing on engineering firms in the infrastructure sector, a practical perspective is also adopted that considers the implementation of BIM methods in real project environments.

In summary, it can be said that the application of BIM in infrastructure projects is a promising tool for promoting sustainability. The results of this thesis contribute to a deeper understanding of the potential of BIM in this area and complement the existing literature by emphasizing the importance of BIM for sustainability in infrastructure planning. It shows that a comprehensive view of BIM application beyond building construction is necessary to capture the full range of its benefits for sustainable infrastructure developments.
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