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Research Article

Sustainable Infrastructure Design Framework through Integration of Rating Systems and Building Information Modeling

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BIM (building information modeling) can be the basis for carrying out various performance analyses. Sustainable infrastructure rating systems are suitable tools for assessing an infrastructure's environmental performance. It is necessary to integrate them in the design process. The research adopted a thorough literature review to follow the development trends, interviews with professionals from the academia and industry, and a critical analysis of technical requirements for integrating BIM tools and infrastructure sustainability rating systems in the design process. This study propagates a conceptual framework for integrating sustainability rating systems by introducing BIM with a sustainability metric plug-in. The adoption of the proposed solution allows for what-if scenarios to better support the incorporation of sustainability into design decisions and the assessment of sustainability at the design phase of the infrastructure project. The framework is used to refine designs and ensure that sustainable goals are met and to demonstrate compliance with regulatory requirements. This paper concludes that greater emphasis should be placed on supporting technical requirements to facilitate the integration of BIM and sustainability rating systems. It defines the possibility of BIM adoption to influence the sustainable project performance in the infrastructure. This framework could streamline the sustainable design process and lead to more integrated infrastructure delivery.

1. Introduction

Infrastructure sustainability has attracted great attention [1]. It is rife with propaganda but requires much greater practical solutions. As the largest sustainability opportunities lie in the planning phase, sustainable design can be a critical success factor. All of these goals lead to more sustainable solutions for the infrastructure and are possible to be achieved with BIM.

Building information modeling (BIM) has been used in buildings for many years [2] and now it is applied across the entire built environment [3]. Sustainable designs adopt BIM as a basis for carrying out the various performance analyses [4]. BIM can potentially support the early design sustainability analysis. The major problem appears to be that it is not defined what infrastructure performance knowledge should be in the BIM. In theory, BIM is well suited to sustainability due to the capacity of BIM to inventory beneficial data for measuring life cycle costs or performing energy analysis. But in practice, a lot of problems have been arising related to interoperability, regulation, and compliance issues.

The objective of this research is to propose a sustainable design approach for infrastructure, focusing on sustainability rating systems as decision-making criteria along with BIM data. This paper analyzes the possibility of integrating rating systems and BIM in sustainable infrastructure design from literature and industry and then presents a theoretical framework that integrates quantitative design data generated from BIM models interacting with performance evaluation in a systematic way. It will give a better insight into the sustainable design process in the context of integration of BIM data and standard performance evaluation in the design stage.

2. Literature Review and Analysis

2.1. Infrastructure Sustainability and Sustainable Design. Elkington considered sustainability as a concept involving the famous triple bottom line—people, planet, and profit [5]. Abidin and Pasquire considered sustainability as an objective including elements of the design, such as energy efficiency, waste minimization, and low maintenance costs [6].

Sustainability is an important criterion in the construction of the infrastructures. The definition of sustainability in the construction sector has been discussed by many authors [7, 8]. Meng et al. referred infrastructure sustainability to life cycle sustained and effective system functionality for urban social, economic, and ecological development [9]. George et al. developed a 4Es (Economic, Effectiveness, Efficiency, and Ethics) and 4 Poles (Economic, Social, Environmental, and Technology) model of sustainability [10]. Similar pillars were also given by Hill and Bowen as social, economic, biophysical (the atmosphere, land, ecological community, and the built environment), and technical (the performance and quality of a building structure) [11]. Aksorn and Charoenngam grouped sustainability factors affecting local infrastructure projects into 6 dimensions: management and administration, information and knowledge, policy and plan, environmental and natural resources, facility and infrastructure, and finance and budget [12]. Booth et al. [13] and Black [14] defined the sustainable transportation system as encouraging recycling in its construction and minimizes and the use of land, minimizing the use of nonrenewable resources and reducing emissions and waste, allowing the basic access needs of individuals to be met safely while ensuring the health of people and the ecosystem, supporting a strong economy and facilitating equality between and within generations. In this paper, the definition of infrastructure sustainability is focused on assured compliance with conventional infrastructure sustainability specification in sustainability rating systems rather than proactive improvement of all sustainability factors.

Many researchers have suggested methods to achieve infrastructure project sustainability. Choguill summarized the 10 principle approaches used and evaluated by a number of countries to facilitate local infrastructure in a cost-effective and environmentally friendly manner in the planning, decision-making, implementation, and management processes [15]. The term sustainable construction was originally proposed to describe the responsibility of the construction industry in attaining "sustainability" [11]. Sustainable design was also adopted by many researchers [11, 16, 17]. They are often used in sustainability concepts.

2.2. Sustainable Infrastructure Rating Systems. The sustainability assessment of infrastructure projects plays a vital role in guaranteeing the success of projects. When examining the sustainability of infrastructure projects, many questions, such as what are the sustainability factors and how those sustainability factors can be measured, need to be subjected to more scientific scrutiny. Each dimension of sustainability should be evaluated. Koo et al. explored the interaction of all aspects of the project during the entire life cycle when conducting a sustainability assessment [18]. Shen et al. introduced a set of key assessment indicators to assess the sustainability of infrastructure projects in China [19].

Different methods are introduced to assess the sustainability aspects of the entire life cycle. Sustainable rating systems have been adopted for this purpose. There are more than 600 rating tools and about 170 evaluation criteria in the building industry [20, 21] such as Leadership in Energy and Environmental Design (LEED) in the US and Building Research Establishment Environmental Assessment Method (BREEAM) in the UK. There have been plenty of research on the interaction between BIM-based sustainability analyses and the building rating systems [22, 23].

Indicators for assessing the environmental, social, and economic performance of infrastructure are vague, and transport-specific sustainability metrics are more difficult to define than metrics for buildings. In the building assessment tool BREEAM New Buildings, for instance, thermal comfort is an aspect, but this aspect is not relevant for the infrastructure. Consequently, building sustainability rating systems could not be simply transferred to the infrastructure sector. Maybe because of this, the development of sustainability rating systems has been relatively slow for the infrastructure sector [24].

An example of a sustainability assessment tool for infrastructure is the Dutch system DuboCalc. DuboCalc is based on the "Assessment Method environmental Performance Construction and Civil engineering Works." This assessment method makes use of the Dutch "National Environmental Database" in which environmental properties of construction materials are stored. The assessment method is in turn based on the European norm EN 15804 "Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products." DuboCalc helps to assess the environmental impact of used materials during the whole life cycle, including winning raw material, transport, construction, operation, maintenance, demolition, and waste treatment. The resulting environmental performance of the construction project is subsequently translated into an environment cost indicator (MKI in Dutch), using a "shadow price method." In this way, the extra "cost" is defined as a result of the environmental impact of materials and structures. DuboCalc is mostly used in national infrastructure projects in the Netherlands.

Currently, a number of different rating systems are adopted to evaluate the sustainable performance of infrastructure [25]. These include but are not limited to the contents in Table 1.

Many of these systems were developed by or for specific agencies with a focus on specific, local environmental needs or context. Several local states and research organizations have set out to develop and implement their own rating systems to measure and quantify the sustainability of their own projects in a regional context. There is no current rating system developed and implemented by any national organization that can be compared with LEED and BREEAM.

Table 1: The state of the practice in infrastructure sustainability assessment.

Nations	Rating systems	Credit categories
United States	GreenroadsTM	Project requirements Environment and water Access and equity Construction activities Material and resources Pavement technologies Custom credits
	FHWA INVEST (infrastructure voluntary evaluation sustainability tool: sustainable highways self-evaluation tool)	System planning (integrate economic, natural, and social goals into long-range transportation planning, etc.) Project design (economic analysis, life cycle analysis, etc.) Operations (internal sustainability plan, energy use, etc.)
	STARS (sustainable transportation analysis rating system)	Project (integrated process, access, etc.) Plan (integrated process, community context, etc.)
	GreenLITES (green leadership in transportation and environmental sustainability)	Safety, health, and equity Sustainable sites Water quality Materials and resources Energy and atmosphere
	Envision sustainability rating system	Quality of life Leadership Resource allocation Natural world Climate and risk
United Kingdom	CEEQUAL (civil engineering environmental quality assessment and award scheme)	Project/Contract strategy (optional) Project/Contract management People and communities Land use (above and below water) and landscape The historic environment Ecology and biodiversity Water environment (fresh and marine) Physical resources use and management Transport
	HTMA-sustainable highways maintenance tool	Sustainable consumption and production Climate change and energy Natural resource protection and environmental enhancement Sustainable communities
Australia	Australian green infrastructure council-infrastructure sustainability (IS) rating system	Management and governance: management systems, procurement and purchasing, and climate change adaptation Using resources: energy and carbon, water, and materials Emissions, pollution, and waste: discharges to air, land, and water; land; waste Ecology People and place: community health, well-being, and safety; heritage; stakeholder participation; urban and landscape design Innovation
	VicRoads INVEST©–integrated VicRoads environmental sustainability tool	Air quality Behavioural change and capacity building Biodiversity Cultural heritage Energy Noise management Resource management Road design Stakeholder management Urban design Water and waterway Management

Issues related to water, energy, materials, and the environment are commonly identified between rating systems but different weights are given to each factor [26]. This checklist in rating systems could provide a foundation for digital sustainability assessment of infrastructures.

2.3. BIM and Infrastructure. The construction and maintenance of infrastructure have resulted in greater demand for natural resources, increased occupation of land, and in negative effects on the ecosystem. The inefficiencies and waste are in large part due to the lack of good quality information [27].

While 3D modeling is gaining increasing acceptance in building design and engineering, the infrastructure domain still heavily relies on 2D drawing-based processes [28]. However, recent research focuses on addressing these limitations by applying the 3D modeling paradigm to the infrastructure domain [29]. Referring to the best practices in the building sector, BIM is seen as a tool that improves efficiency and quality, reduces mistakes and rework, enables quantitative analysis, and facilitates effective communication. There are more research works and papers on 3D and 4D implementation in the infrastructure projects and the subject is highlighted in some pioneering reports [30]. Olde Scholtenhuis et al. adopted a 4D CAD-based method as a BIM tool to tackle coordination issues of urban utility works [31]. Hartmann et al. implemented BIM-based tools on a large infrastructure project, indicating that implementing BIM requires practitioners to align the BIM-based tools and well-established construction management work processes in a construction project [32].

Although BIM uses in infrastructure projects lag several years behind building construction, according to McGraw-Hill Construction [30], nearly half of the respondents (46%) report that they are using BIM on their infrastructure projects and 67% have achieved positive value. 78% of survey responders are using BIM on at least 25% of their infrastructure projects and these numbers will grow dramatically in the future. In Europe, the percentage of contractors that are using BIM on infrastructure projects (roads, bridges, tunnels, dam, and water) is growing in the UK (33%), France (19%), and Germany (16%), which is a little higher than that in the US (14%) [33]. More than half (55%) of the companies focusing on infrastructure projects in Australia and New Zealand claim to achieve over 25% return on investment (ROI) of BIM, whereas companies mainly doing buildings report a less positive ROI (only 29%) [34].

2.4. BIM and Sustainability. In the investigation of Bynum et al., most respondents indicated that BIM was used predominantly for the project coordination and visualization [35]. Sustainability was not a main application of BIM. BIM is mostly used for energy simulation of the building envelope (materials, lighting, and etc.). Kryegiel and Nies indicated that BIM can aid sustainable design in the aspects of building orientation, building massing, daylighting analysis, water harvesting, energy modeling, sustainable materials and site, and logistics management [4]. The majority of BIM tools capture three main engineering aspects: thermal load (heating and cooling) calculation, computational fluid dynamics (air flows in and around buildings), and interior lighting and acoustics simulation. The mature environmental analysis tools integrated within BIM tools have already been available in buildings.

Sustainability efforts are mostly based on quantifiable data, whether immediate or long-term, and BIM has the capacity to handle volumes of data. Apparently, sustainability elements in the BIM system lie in the inbuilt relationship and constraints, which improve the design and construction outcomes and provide a reasonable feedback loop from precedence [36]. BIM can be used to view and organize monitored data. For example, air-quality sensors can be placed in the facility to input data into BIM, resulting in the ability to monitor and analyze current conditions [37]. Ibrahim and Krawczyk have demonstrated the benefit of embedding building code requirements into the BIM software, making the review process much smoother [38].

Zahran et al. devised a new 3D visualization approach for modeling air quality before and after the implementation of potential urban transport schemes [39]. The European project Sustainable Energy management for Underground Stations (SEAM4US) developed an intelligent environmental aware energy management system for underground stations [40]. Yigitcanlar and Dur introduced the Sustainable Infrastructure, Land Use, Environment, and Transport (SILENT) model [41]. It is a GIS application for urban sustainability indexing and can improve the cooperation in decision-making among strategists, and planners bent on promoting sustainable development. All these approaches are useful for accessing the infrastructure sustainability; however, they disregard the support of scientific rating criteria like sustainable infrastructure rating systems.

BIM and sustainability are conceptually related and synergetic. Early integration of sustainability considerations into a policy and early involvement of BIM in the project development process is the key to ensuring that sustainable outcomes are achieved.

2.5. Literature Review Discussion: Identification of Research Gap. There is much research on the subject of sustainability and BIM in infrastructure projects separately. However, few authors highlight the contribution of BIM towards infrastructure sustainability, which can be seen as a lack of awareness of the potential of BIM as a catalyst to enhance sustainability and an unrealized relationship between sustainability vision and BIM objectives.

The design phase should be considered as the first stage for achieving sustainability [42]. Many studies have recommended that environmental issues should be fully incorporated into project planning and design to mitigate environmental impacts [43]. Embedding environmental knowledge contributes significantly to sustainable design. Sustainability analysis methods and criteria should be configured as early as possible without relying on detailed design information generated by the designers when discussed in detail in the paper [44].

Infrastructure sustainability rating systems contain all aspects of the infrastructure sustainability and their scientific relations. They can be used as benchmarks in order to compare different design choices and scenarios to support the decision-making and achieve continuous improvement. Creating BIM means creating the infrastructure digitally in the virtual environment, which needs to be linked with a database of project information. So in theory, any information required for testing "what-if" scenarios to better support the incorporation of sustainability and assessing of sustainability in the scheme is necessary.

There is little research bridging BIM model data and the early design stages in which information about sustainability decision-making factors run throughout the infrastructure life cycle. The successful implementation of BIM and sustainable building rating systems add heuristics to the integration of BIM and sustainable infrastructure rating systems.

3. Research Methodology

The paper is a qualitative research. As little theorization has been done on the BIM implementation on the infrastructure sustainability, we seek to contribute to the enrichment of the field by a literature review and interviews with representatives.

First, a thorough literature review of connections between three key topics (infrastructure, sustainability, and BIM) was carried out to follow the state of the art and identify the knowledge gap. A knowledge gap of lacking using BIM for infrastructure sustainability was identified. This problem can be overcome by the integration of BIM tools and sustainable infrastructure rating systems.

The interview method is a useful way to "learn from strangers" and obtain additional insights of interviewees' experiences [45, 46]. Interviews are often used to probe perceptions, attitudes, and experiences of participants in BIM research [47, 48]. Interviews with professionals from the academia and business were conducted for perceptions of the existing situation, and industry needs analysis. The informants were chosen because they have rich academic or industry experience and interest in applying BIM and sustainability concepts in infrastructure projects. Only firms that had completed at least one project using BIM tools were included. Twenty-nine interviews from Europe and China were conducted to fully reflect the current industry needs. The interviews were designed to probe their perceptions, attitudes, and experiences relating to the sustainability when implementing BIM in infrastructure projects.

A framework is often highlighted to organize domain knowledge and facilitate the elicitation of tacit knowledge [49]. Many BIM frameworks are introduced as a research and practical foundation for scholars and industry stakeholders [50, 51]. Findings from these two stages were used to conceptualize the framework that bridges the knowledge gap and satisfies the industry needs for integrating rating systems and BIM in the sustainable infrastructure design. Finally, a critical analysis and validation of technical requirements with part of the interviewed professionals in light of the industry needs were given. The technical requirements were categorized for the sustainability-supported BIM system as a reflection on the above framework.

4. Interview Research: Industry Needs Analysis

To define and design the framework for integrating BIM and sustainability rating systems, semistructured qualitative interviews with key players in the infrastructure industry were used to collect data. Of the firms included in the research, fifteen are based in Europe and fourteen are based in China, including Hong Kong. Of the informants in this study, there are three clients, fifteen designers/consultants, five constructors, and six researchers. Two clients, five designers/consultants, three constructors, and five researchers are from Europe and one client, ten designers/consultants, two constructors, and one researcher are from China. Details about the respondents are given in Tables 2 and 3.

4.1. Interview Results

4.1.1. Awareness and Interests. All of the respondents agreed with the national and international interests in the integration of infrastructure sustainability and BIM. The general revolutionary role of BIM is recognized and one or two examples of common BIM applications such as visualization and clash detection can be given easily. Regardless of the depth of the available BIM knowledge, their companies have started with the deployment of BIM and are eager to gain more experience and to make more breakthroughs in their projects.

However, only the group of the researchers who have studied the topic of sustainability and clients were well aware of the concept of infrastructure sustainability. Their understanding of sustainability was broader, containing environmental, economic, and societal aspects than practitioners. Designers, consultants, and contractors answered that they became aware of the importance of infrastructure sustainability, but they acted in their projects in a passive manner just following the existing regulations. In contrast, they were not always well aware and they usually had an incomplete understanding of sustainability.

4.1.2. Current Situation. This response to the interview showed that the integration of sustainability and BIM has not been evenly promoted over the whole construction sector. The awareness of the integration of infrastructure sustainability and BIM stayed at a lower level.

The biggest reason for this is the different focus of strategies and targets. The informants said that the main targets of sustainability in buildings were reductions of energy consumption and greenhouse gas emissions as a percentage over the baseline in the construction industry. However, the infrastructure is not an energy-intensive and greenhouse gas-emissive industry like building, but a material-intensive industry. In current strategies and targets,

Table 2: Overview of Interviewees: features of respondents in Europe.

No.	Role	Organization
1	Project manager	Government
2	Project manager	Government
3	Designer	Engineering consultancy
4	Designer	Architectural design firm
5	Designer	Architectural design studio
6	Consultant	Architectural design studio
7	Consultant	Infrastructure consultancy
8	Project manager	Contractor
9	Project manager	Contractor
10	Project manager	Contractor
11	Researcher	Consultancy
12	Researcher	Applied scientific research institute
13	Researcher	University
14	Researcher	University
15	Researcher	University

Table 3: Overview of Interviewees: features of respondents in China.

No.	Role	Organization
1	Client	University
2	Designer	Architects and engineering institute
3	Designer	Municipal engineering design institute
4	Designer	Design and research institute
5	Designer	Architectural and civil engineering design firm
6	Consultant	AEC technology company
7	Consultant	Engineering consultancy
8	Consultant	University
9	Consultant	AEC technology company
10	Consultant	Engineering consultancy
11	Consultant	Research Institute of Building Science
12	Project manager	Contractor
13	Project manager	Contractor
14	Researcher	University

material and resource targets are not suggested for the infrastructure industry.

Because of the late dissemination of BIM in the infrastructure, it is still in an early phase to evaluate the achievement of the integration of infrastructure sustainability and BIM. The informants gave the positive view that BIM had attracted a big amount of attention in the infrastructure industry. However, the informants gave the negative view that the current policies of sustainability have not led to the change for the integration of sustainability and BIM.

4.1.3. Barriers

(1) Government Agencies' Willingness and Effort. The informants pointed out the unsystematic policy by the government as one of the biggest barriers. In fact, the government provides enormous efforts for BIM and infrastructure sustainability but fails in less apparent criteria in a passive manner. The government just encourages public building sectors to reduce energy and greenhouse gas emissions. When it comes to the infrastructure, there are no determined goals and guidelines. In the future, more and more public projects are required to use BIM. But the definition of using BIM is so vague that it is unclear whether sustainability will be addressed as well. Less systematical criteria in policy and less apparent standards cause the industry to be doubtful about the way forward to the integration of infrastructure sustainability and BIM.

(2) Client Attitude. One of the critical reasons for the low interests is the initial and additional cost for the integration of infrastructure sustainability and BIM. Every participant has a goal in terms of creating profits from their projects. Higher sustainable requirements and BIM investment can increase cost when the work processes are changed and new software must be acquired continuously. When talking about the performance assessment, cost, time, and quality are always important subjects and often also customer value and environmental issues. Due to the complexity in sustainability analyses, designers usually choose manual calculation, with traditional paper maps, unless a special team for sustainability is assigned. It takes time, skills, and efforts of architects to submit a sustainability report. It is not easy to see how BIM is paying off.

(3) Performance Evaluation. When the policy for green building was established, the policy was evaluated with relevant methods like LEED or BREEAM to meet the utmost vision and goal. In a similar manner, the policy of sustainable infrastructure needs performance measurement. The informants pointed out that the necessary criteria and performance measurement tools for sustainable infrastructure are still missing. When asked about their efforts in carbon emissions reporting and reduction, most of the informants hummed and hawed, giving no definite reply. Voluntary sustainability targets have proven elusive and there is much more to be done.

(4) Supply Chain Integration. Supply chain partners are challenged to identify sustainable alternatives both in the upstream and downstream processes. If the client has no ambition for BIM and sustainability, the designer may choose a traditional approach and ignore the consideration of sustainability. If the designer has not put the concept of BIM and sustainability in the plan, the contractor has only limited possibilities to deliver sustainable construction. If there are no efforts from the upstream, it is quite difficult for the asset manager to achieve sustainable development in the BIM way.

(5) Sustainability Knowledge and Expertise. Sustainability is hard to define and can be seen as a vague concept. Most informants confirmed that currently the integration of infrastructure sustainability and BIM is not clearly defined. BIM for environmental infrastructure sustainability is not known amongst the informants. Some were very enthusiastic. Others were more cautious, stating that there are many parameters that determine sustainability, but not all of these factors are taken into account by BIM. Moreover, there is not much willingness to document lessons learned

from infrastructure projects for sustainability as confirmed by the experience shared by a few informants.

There is still not a clear and consistent understanding of the concept among practitioners and academia in this survey. The academics were ambitious for taking sustainability into consideration and were not satisfied with the carelessness of the industry. The informants from the industry had different views on sustainability. Most of them had not realized that BIM has the ability to facilitate the infrastructure sustainability. Sustainability becomes a byproduct rather than becoming the main goal of BIM. This knowledge gap between the academic and the industry will limit the promotion of BIM.

(6) BIM Technology Readiness Level. The paradigm of integration of infrastructure sustainability and BIM stays in the beginning phase. Informants from the client insist most of the data for sustainability are stored in GIS databases. BIM and GIS are not always compatible. The approach for harmonization of BIM and GIS is still discussed. This means that BIM cannot fully support the sustainable solutions from the perspective of technology. BIM is still mainly seen as a tool for visualization by most respondents. With regards to BIM, most participants agree that the available software is currently less focused in the infrastructure construction.

4.2. Summary. In this section, the results of a number of interviews with stakeholders are presented. The results represent the opinions of the stakeholders about the integration of infrastructure sustainability and BIM. The informants expressed that there are pros and cons of the current status of the sustainable infrastructure design and BIM. The interview results confirmed that BIM implementation was encouraged not only for its efficiencies but also for environmental reasons. After analyzing the responses of different types of informants (clients, designers/consultants, constructors, and researchers), gaps in practices were revealed, which are discussed from the categorization of barriers in key thematic areas. Together, these barriers have an impact on the infrastructure sustainability and BIM. The interview data suggest that the integration between BIM and sustainability evaluation criteria should be established.

5. Framework for a Sustainability-Supported BIM System

In this section, a theoretical framework for a sustainability-supported BIM system is presented. The main elements of the framework are presented in 5.1, followed by a high-level architecture in 5.2.

5.1. Framework Elements. As shown in Figure 1, the proposed framework consists of three major components: BIM model user interface, sustainability rating processor, and sustainability rule database. They are interrelated with each other in a way that data are shared in an automatic and efficient way.

5.1.1. BIM Model User Interface. Given a large amount of environmental data that need to be compiled for effective suitability analysis in sustainable infrastructure rating systems, BIM is used as an effective tool for organizing, storing, analyzing, displaying, and reporting the information.

The basic skeleton of the framework is based on the infrastructure BIM model in BIM model user interface. BIM model user interface allows designers to input the basic information of an infrastructure project. Data stored in a well-established BIM model provide enough information and specialized expertise to complete such a computationally complex rating and analysis, for example, materials and resources in GreenLITES (Green Leadership in Transportation and Environmental Sustainability) and using resources: energy and carbon; water; materials in Australian Green Infrastructure Council—Infrastructure Sustainability (IS) Rating System. Another feature of the BIM model user interface is the provision of the evaluation results. A snapshot of the evolving design object is defined without complicated data for subjective sustainability-related decision-making. The user interface can interact with the BIM model to generate real-time visualization.

5.1.2. Sustainability Rule Database. As the second component of the framework, the rating systems are used as the design criteria for choosing the best program or checklist of the sustainability factors. Sustainability rating systems are suitable tools for assessing an infrastructure's environmental performance. The existing sustainable infrastructure rating systems have covered almost every aspect of sustainability in the domain of the infrastructure. A defined list of indicators cannot make a future-proof assessment system. The rules in a sustainable infrastructure rating system are often expressed in a natural language such as quality of life in envision sustainability rating system. To convert the rules into a database, the conditions and properties from the rules should be extracted and all properties contained in the rules should be distinguished. BIM appears as a good resource for providing the needed information. Digital mechanisms of BIM will help enhance its usability to the maximum level.

5.1.3. Sustainability Rating Processor. The sustainability rating processor contains all the evaluation formulas, extracts the required information from a BIM model, and calculates the value demanded by rating systems. On the other hand, the sustainability rating processor can retrieve the evaluation results from the sustainability rule database and display the results in a BIM model with highlighted elements.

Sustainable infrastructure rating systems require significant amounts of specific information typically carried within BIM design tools, but they are not able to communicate easily and efficiently with existing BIM authoring tools. Only the particular BIM data contain the necessary information to perform corresponding performance simulations. Therefore, the function model extractor is needed.

Ideally, the designer could directly access the data of the BIM model, but the rule compatibility can be highlighted as

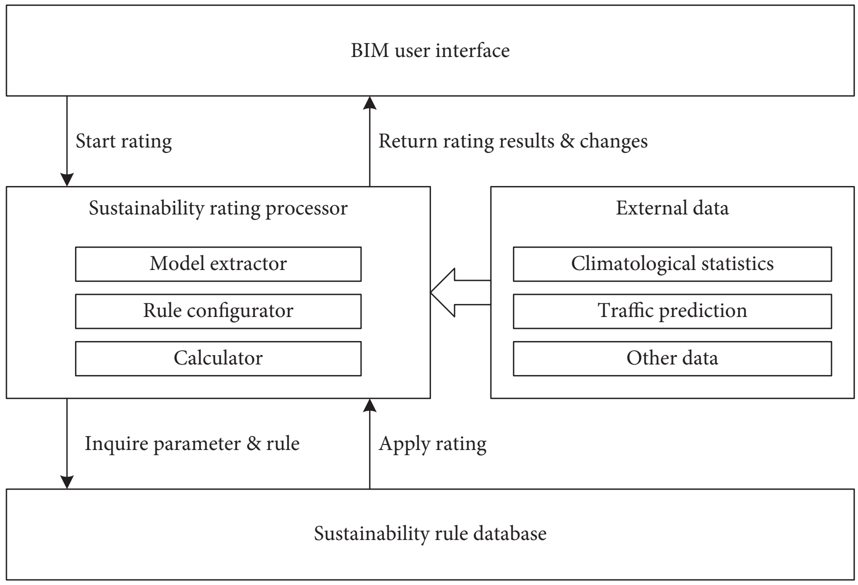

Figure 1: A framework integrating BIM and sustainable infrastructure rating systems.

one of the main difficulties involved in current rating systems. This can be solved by the function rule configurator. BIM models can be comprehensive including sustainability-related requirements and can be checked for compliance with sustainability.

A comprehensive assessment of all aspects of sustainability requires an evaluation to determine whether sustainability has been sufficiently incorporated into the plans. This process is carried out by the function calculator.

However, besides BIM models, other kinds of external data are required as supplementary elements. The input data to the sustainability rating processor is supplemented by another component—the external data. The meaning of external data here is broad enough to cover climatological statistics (climate change in HTMA-sustainable highways maintenance tool), traffic prediction (transport in CEEQUAL), and so on. Different types and numbers of external data can be multiplied and expanded to the urban level in support of the infrastructure quality. Correlations can be analyzed between the external data and the design quality in the framework of sustainability rating systems.

5.2. Framework Design

5.2.1. Architecture. Learning from experiences from sustainable building design, two lessons are drawn. In order to deliver sustainable design, the first way is to optimize the energy use and material consumption in a certain built environment, and the second way is to try an alternative new method which is more cost-effective than the original one. The former way depends on a computational test using large quantities of data from the design, whereas the latter way needs a quick what-if scenario visualization. The proposed BIM-based sustainable performance calculation framework is based on three components:

(1) BIM user interface which supports 3D object-based BIM models with an underlying database of component information,

(2) sustainability rule database which contains all the items in the checklist in sustainable infrastructure rating systems, and

(3) sustainability rating processor that is accessible from the BIM software platform and from infrastructure sustainability rating systems, and the external data excluding the categories contained in the BIM software platform but required in the sustainable performance databases.

Six major steps of BIM analysis for sustainability issues in the guidance of sustainability rating systems include (but not limited to) the following:

(1) definition of the proper parameters and rules for the analysis,

(2) definition of data needs,

(3) acquisition and extraction of data, including external data, if necessary,

(4) configuring BIM models containing the data with rules from the sustainability rule database,

(5) applying to rate and return results, and

(6) refinement of the model.

Following the above principles, a framework integrating BIM and sustainable infrastructure rating systems is developed as shown in Figure 1.

Take FHWA INVEST (infrastructure voluntary evaluation sustainability tool: sustainable highways self-evaluation tool) as an example. The Sustainability rating processor implements the sustainability rating with the help of the model extractor to extract needed data from the BIM model. To facilitate infrastructure sustainability rating, the rule rating process is separated into three functions: the model extractor for model preparation, the rule configprator for rule interpretation, and the calculator for rule execution. These three components are highly interrelated to construct a systematic view of the sustainable design.

This rating system has three main rules: system planning, project design, and operations. The rule configurator facilitates the management of rules. It serves as the connection between BIM models and the sustainability rule database. It helps establish the consistency of an infrastructure element's functional and physical attributes with its sustainability requirements and convert standards into rules readable by BIM models. Some analysis can be done directly (economic analysis in project design). The query methods are stored in XML format. Such capabilities are already available through gbXML (the Green Building XML schema), which helps facilitate the transfer of properties stored in BIM models to energy analysis tools (life cycle analysis in project design and energy use in operations). In the framework, the BIM model needs the addition of the climatological statistics (natural goals in system planning), traffic prediction (long-range transportation planning in system planning), and other data to be used as a source for rating. The external data hold one of the key positions in the integration. The calculator uses parameters and rules in the sustainability rule database and organizes BIM model data to perform compatible rule evaluations and then sends the evaluation results to the BIM user interface. Then, the rating results are sent as a conclusion to the BIM model user interface for visualization. Through the BIM model user interface, the evaluation result can be illustrated in both the BIM model and data tables for assisting sustainable infrastructure design.

The decision-making activity will be based on the configured model under the assessment of the chosen sustainable infrastructure rating system. If there is still lacking information for evaluation and decision-making, the model extractor will trace back from the original BIM model and the external database. If decision-makers are not satisfied with the results, the sustainability rating processor will go back to where the environment is saved, thereby permitting the correction of a previous plan. After several loops, the best-performed model can be selected as a candidate for the further development.

5.2.2. Operational Mechanism. The dynamic changes are not considered in the traditional method. BIM provides a platform capable of capturing these dynamic data affecting the performance and level of service in infrastructure projects. The architecture of the framework, in reality, forms a learning cycle for critical thinking. Figure 2 illustrates the sustainable design cycle. The original design program is translated into BIM models and these BIM models then act as the raw information on which decisions are based. Related rating systems and local environmental data are processed to orient for further analysis and revision. The same loop and logic are repeated continuously until the optimal decision is obtained fully conformant with these standards requirements. Finally, infrastructure design decision-makers gain an advantage of full awareness of the situation and flexible fitting the local sustainability rating system.

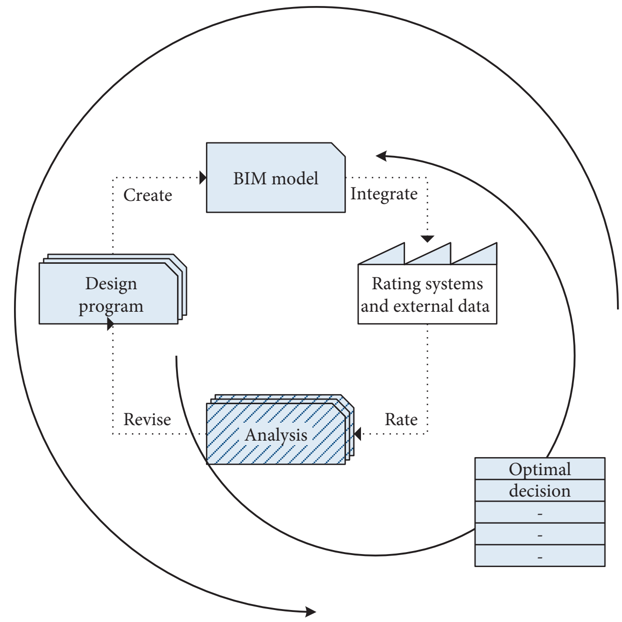

Figure 2: Sustainable infrastructure design cycle.

Continuous addition of external data and evaluation can directly go back to the design phase data and decision-making moments with ease using this framework. By upscaling to multiple project sites in an urban context, the framework can integrate both rich local environmental data and custom-made sustainability rating systems to monitor and analyze the sustainability performance of the infrastructure project. The framework also enables tracing back to the design data of certain time, in order to continuously improve decision-making in the infrastructure life cycle management. In this way, the integration solution aims to change the sustainable design from a linear process to an iterative and continuous process.

6. Framework Validation and Technical Requirements

The prototype of Figure 1 was validated by an additional dialogue with the interviewed professionals who expressed their interest in the potential framework in the prior interviews. The validation showed that the framework adequately responds to the needs of the current industry because it helps to make more informed decisions and to have all the information needed in one place. In addition, respondents highlighted the time savings in the sustainability checking and the possibility to store, organize, and classify information, and considered it as a good guide for the decision-making process, decreasing the likelihood of making a wrong decision in this way.

6.1. BIM Model Management Related Requirements

6.1.1. Data Repository. The data capacity and efficiency of the framework rely on the full access to the data repository.

Different parts of the infrastructure can be modelled with different BIM authoring tools. These federated data repositories should be linked to each other. The sustainability-supported BIM system should be supported by a centralized data repository of the infrastructure project.

6.1.2. External Data Access. Projects tend to be run under large document management and approvals systems. The CAD or BIM data are only one part of the total information store. The large scale of these projects tends to demand integration with GIS and mapping type information. Architects can input supplementary data into the BIM models that help the design team understand issues related to the climate, location, and surrounding environment.

6.1.3. Interoperability-Based Specifications. Interoperability-based specifications allow each object to be uniquely identified, preventing misunderstanding, confusion, and duplication. IFC is the only nonproprietary intelligent, comprehensive, and universal data model for built assets [52]. However, IFC files only contain the information that was processed at export and has the potential loss of information during export [53]. The sustainability-supported BIM system should enable efficient integration to interact between different discipline-specific models.

6.2. Sustainability-Related Requirements

6.2.1. LCA-Based Calculation Rules. Sustainable infrastructure rating systems facilitate to consider decisions and activities which occur during the life cycle of a project. It applies to a broad range of transportation life cycle phases or to focus primarily on one or two phases [54]. Design and realization choices have a significant effect on the environmental impact of infrastructural works. Therefore, the ICT tool should be developed to calculate the environmental impact of the different infrastructure designs, based on material and energy use during the whole life cycle.

6.2.2. Customized Scorecard. In practice, team members need to determine whether the given criteria are relevant to the project and whether they should be used in rating. The framework should allow rules that do not apply to a given project to be removed from the total amount of possible points. Sustainable infrastructure rating systems facilitate the assignment of weights to various criteria or allow the user to apply customized credit weights when evaluating the sustainability of the project [54]. This should be embedded in the rule configurator of the framework.

6.3. Implementation Issues. According to the analysis before, one infrastructure sustainability rating system that can integrate it all is impossible. So locally used BIM software/platform for sustainability capability should be developed. Checking the infrastructure design models for compliance with sustainability rating systems must be developed further.

The baseline of the infrastructure performance shall be generated by simulating the infrastructure with its actual orientation. BIM software companies can develop sustainable infrastructure rating system code-checking software plug-ins embedded in BIM software tools. Compared with outsourcing to a third party to conduct the environmental analysis independently, it is beneficial for designers to receive feedback directly from the BIM model user interface and improve their designs continuously.

7. Discussion

7.1. Theoretical Implication. Interviews with professionals in this research demonstrate that the use of rating systems to attain higher degrees of sustainability is certainly becoming more commonplace than ever before. The benefits of BIM pertaining to productive data storage and data computation are greatly advantageous throughout the design processes. This study complements the current literature by indicating that rating systems and BIM extends the designers' perception via evaluation, navigation, and simulation, and at the same time offers alternative ways of understanding the sustainability, as current assessment methods for infrastructure sustainability are often based on the designer's judgment [55]. This study contributes to the sustainability and BIM research in infrastructure projects by presenting a theoretical framework. The framework enriches the body of knowledge of green BIM. Prior studies have found that green BIM can enhance the environmental sustainability of buildings [56, 57]. We seek to contribute to the enrichment of the field by building conceptual bridges between rating systems and BIM in the infrastructure design.

7.2. Practical Implication. The research provides a new perspective in managing the BIM data of infrastructure projects. The framework for a sustainability-supported BIM system opens the door for more integration of BIM in the infrastructure sector. It helps to enhance environmental management performance of infrastructure projects as they can base their work on the analysis of sustainability in the design stage and as they progress. Rating systems and BIM are suggested to be integrated into the infrastructure design, which provides the ability to better analyze and visualize the data infrastructure projects [58]. A more proactive attitude toward sustainability and more powerful BIM data processing capability is essential to achieving the combination in infrastructure projects [59].

7.3. Limitations and Future Research Directions. The paper opens the area for further research but it is not yet ready for implementation in practice. The future integration of BIM and infrastructure sustainability rating systems will be completely interactive with key infrastructure information, climate information, traffic requirements, and environmental impacts. Then, once the infrastructure is completed, the BIM model will create an opportunity for the asset management feedback loop. The proposed framework is conceptual in nature but provides the underlying foundation for infrastructure designers to consider how BIM can lead to a sustainable advantage.

8. Conclusion

As with earlier studies on literature and interviews, this study found that people are interested in the effect of BIM for infrastructure sustainability. However, BIM is used for design and construction management more often but not necessarily for sustainability purposes. This research proposes a theoretical framework for a sustainable design approach for integrating BIM rating with sustainability rating systems. From a theoretical viewpoint, the underlying premise of the proposed framework introduces a new paradigm for the sustainable design of infrastructure. The proposed framework will enhance the sustainability-supported BIM system research and development and better promote intelligent and automated sustainable design. One of the key contributions of the framework is to propose a process in which BIM is used as an accelerator for innovation in the infrastructure project sustainability improvement. The framework especially focuses on the integration of various static (rating systems) and dynamic (BIM) data in terms of sustainable design decision-making considering environmental sustainability. Another contribution is the integration of sustainable infrastructure rating systems and the feedback loop to accelerate optimal decision support. It provides an insightful view of the infrastructure design process with the aid of BIM tools and rating systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Previous versions of this paper were presented at the CIB W78 conference 2015.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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