

BIM-based environmental impact assessment for infrastructure design projects

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Abstract

Sustainability is becoming a key factor in the decision-making process of infrastructure projects throughout their lifecycles. In particular, the Environmental Impact Assessment (EIA) in the design phase is becoming a matter of significant importance, for both public and private sectors, given the long-term impacts of design decisions on the environmental performance of infrastructure projects. Nowadays, clients frequently demand EIA of new designs and designers/contractors are compelled to indicate how sustainability concerns are incorporated in their design choices. However, in the current highly fragmented design processes, the EIA is normally conducted as an isolated step at the end of the design loop by sustainability experts. This fragmented process creates a disconnect between the EIA and other aspects of design evaluation which renders the improvement from the sustainability perspective cumbersome and challenging. Also, this fragmented process necessitates a feedback loop between sustainability experts and other members of the design team. This dynamic is not conducive to raising the global sustainability consciousness in the entire design team, especially in the designers. An integrated approach towards the EIA allows designers to strive for improved sustainability in every step of the design process. In recent years, Building Information Modelling (BIM) provides the basis for such an integrated approach towards design evaluation. However, numerous studies have shown that the EIA is not yet fully integrated in the current BIM-based design process of infrastructure. This research aims to develop a framework for performing real-time EIA during the design process. The framework allows designers to run an automated EIA at any point of the design stage and immediately assess the Environmental Impact Score (EIS) of their design choices. A prototype is developed and tested on a case study to indicate the feasibility of the proposed framework. The framework is assessed in terms of functionality, ease of use, scalability and contribution to raising sustainability consciousness through a workshop with experts. It is shown that the framework is able to quickly provide designers with accurate information about the environmental impact of all objects in infrastructure design projects. The workshop with experts showed that the tool clearly makes it easier to perform the EIS assessment compared to the existing, highly fragmented, process. This allows the design team to use this assessment on the same level as other design parameters in the decision-making process. Moreover, the framework helps to (1) raise the sustainability consciousness of the entire design team and (2) facilitate the implementation of EIA for infrastructure projects.

Keywords: Environmental Impact Assessment, BIM, Infrastructure

1 Introduction

The construction industry has a large impact on the environment. Different studies showed the high contribution of the construction industry on energy consumption, raw material use and CO₂ emission [1]. The Architecture, Engineering, and Construction (AEC) industry is responsible for 40% of the total energy use, 32% of CO₂ emissions, and 25% of the generated waste in Europe annually [2]. Because of this high negative impact on the environment and the growing awareness on environmental protection, there is a sense of urgency for the construction industry to become more sustainable in their projects and work processes [3].

Evaluating the environmental impact of a design is often done through a Lifecycle Assessment (LCA). The LCA, as described in ISO 14040, evaluates the potential environmental impact of a product or system throughout its complete lifecycle [4]. However, this assessment is time-consuming, complex and requires a large amounts of data [5]. Therefore, the LCA is often performed at the end of the design phase when all required information is available. This means that design choices with the highest potential environmental impacts are already taken and therefore, it is too late to incorporate the environmental impact in the decision-making process [6~8]. This fragmented process creates a disconnect between the assessment of the environmental impact and other aspects of design evaluation which renders the improvement from the sustainability perspective cumbersome and challenging. Also, the current workflow necessitates a feedback loop between sustainability experts and other members of the design team that is not conducive to raising the global sustainability consciousness in the entire design team, especially in the designers. In recent years, Building information modelling (BIM) has emerged as a potential solution to decrease the effort needed to perform a LCA [9]. There have been numerous studies on BIM-based LCA applications [9, 10, 25, 26]. However, despite the existing interest for BIM-based LCA in infrastructure design, BIM is mostly used for design and construction management purposes [12]. On this premise, there is a clear gap in the use of BIM for an integrated LCA in the current design process of infrastructure.

This research aims to present a framework to integrate the Environmental Impact Score (EIS) assessment in infrastructure design projects by using BIM. The framework offers an approach to (1) automate the EIS assessment of a infrastructure design, and (2) visualize the results inside the BIM environment. In this fashion, the environmental impact of design choices is presented on the same level as other design parameters. This enables the use of the EIS of a design in the decision-making process directly by the designers and, thus, increasing the awareness of designers about the environmental impact that their decisions carry.

The paper is structured as follows. First, a literature review is presented to identify the current state-of-the-art in terms of sustainability in the construction industry and BIM-based LCA. Second, the proposed framework for a BIM-based EIS assessment is presented. Third, the proposed framework is implemented and tested on a case study. Finally, the results, discussion and conclusion are presented where the most important findings, limitations and future research possibilities are discussed.

2 Literature review

2.1 Sustainability in the construction industry

The concept of sustainability was first introduced in 1972 on a United Nations (UN) conference to discuss environmental issues [13]. Over the years, different definitions of sustainability have been proposed. The definition that covers the ‘triple bottom-line’ of sustainability comes from the American Society of Civil Engineers (ASCE) [14]. According to this definition, “sustainability is a set of environmental, economic, and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural, economic, and social resources. With the high raw material usage, energy consumption and waste generation, the construction industry has one of the highest environmental impacts across all industries. The assessment of this environmental impact is often done through a LCA as this is considered to be the most suited method to quantify the environmental impact of material use, energy consumption and waste generation [15].

2.2 Lifecycle Assessments in the construction industry

The LCA assesses the environmental impact of a design during its full lifecycle; from raw material extraction to construction to demolition [16]. According to the ISO 14044 standards [4], a LCA comprises four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation [4]. However, the LCI and LCIA are often combined by multiplying the material quantities of a model with pre-determined values from a database [9].

LCA in the construction industry are often performed by using rating systems. In 2012, there were already more than 600 rating tools and 170 evaluation criteria in the building industry [17]. Examples are Leadership in Energy and Environmental Design (LEED) in the United States and Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom. However, the development of rating systems for infrastructure was relatively slow compared to the building industry [12].

In the early 2000s, it became clear that there was a lack of tools like LEED and BREEAM for infrastructure projects. This initiated the development of Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL) that was led by the Institution of Civil Engineers from the United Kingdom. Currently, CEEQUAL is an integral part of the UK’s construction industry and its strategy towards sustainable development [18]. At the moment, CEEQUAL is by far the most used rating system for infrastructure sustainability with over 260 projects certified up to 2016 [19]. CEEQUAL is an assessment that consists of 12 indicators which are a combination of environmental and social indicators [20]. Other countries developed similar rating systems that are often tailored to specific agencies to fit the local context and needs [12]. The four most common rating systems are shown in Table 1.

Table 1: Common infrastructure sustainability rating systems (Adopted from [12], [21])

Rating system	Country	Type of infrastructure	Considered sustainability topics
GreenRoads	United States	Roads	Project requirements; Environment and water; Access and equity; Construction activities; Material and resources; Pavement technologies.
Envision	United States	Any	Quality of life; Leadership; Resource allocation; Natural world; Climate and risk.
CEEQUAL	United Kingdom	Any	Project strategy; Project management; People and communities; Land use and landscape; Historic environment; Ecology and biodiversity; Water environment; Physical resources; Transport.
IS rating system	Australia	Any	Management and governance; Using resources; Materials and waste; Ecology; People and places; Innovation.

Another example of an Environmental Impact Assessment (EIA) tool is DuboCalc. DuboCalc is software developed by the Dutch Directorate-General for Public Works and Water Management [22]. The assessment methodology of DuboCalc is based on the European norm EN15804 “Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products” [12]. DuboCalc uses the National Environmental Database [23] which contains environmental properties of construction materials (e.g. Global Warming Potential). DuboCalc translates these properties to Environmental Impact Scores (EIS) by multiplying them with a fictional cost for the environment [24]. Based on the quantities of a design, DuboCalc is able to calculate the environmental impact of the design and present this in terms of an EIS (in Dutch: MKI). This indicator can be described as a “shadow price” that shows the extra costs of a design for the environmental impact. In The Netherlands, DuboCalc is the main method to evaluate the sustainability performance of infrastructure projects [12].

There have been numerous studies that compared different rating systems. Doan et al. [25] found that there are large differences in scopes of different systems. While some systems only cover the environmental pillar of sustainability, others include social and economic aspects as well. However, there is no rating system that thoroughly assesses all three pillars. Moreover, Meex et al. [15] observed that most sustainability assessment tools are developed for end-product evaluation. This means that the assessment is only possible when the design phase or even the construction phase is already finished. However, decisions that have the highest impact on the sustainability of a design are often made in an early phase of the design [6~8]. Therefore, an EIA can be extremely valuable in the early stages of a design.

Meex et al. [15] found that LCA-based EIA tools can be extremely valuable in the early design phase of a building project. The study identified several requirements to be able to apply these tools. First, a simplified LCA is required and second, the usability of LCA software should be improved to fit in the design work practices.

2.3 Lifecycle assessments and Building Information Modelling

2.3.1 Building information modelling (BIM)

Because of the increasing difficulty and complexity of construction projects, Building Information Modelling (BIM) has emerged to optimise, automate and modernise the traditional work practices of the industry [2]. BIM is becoming more and more common in the construction industry. In the United Kingdom, it is even mandatory to use BIM in public projects [26]. The concept of BIM can be defined as a set of policies, processes, and technologies which translates into a working methodology that is able to manage 3D drawings and other project data in a digital environment during the entire building life cycle. The use of BIM is an integrated process where functional and physical characteristics of a project are managed by digitally simulating the real construction process of a project [27].

2.3.2 LCA-BIM applications in the design phase

When the extra dimension of environmental sustainability is added to the BIM philosophy, this can be described as green BIM. This extra dimension includes the assessment of the environmental sustainability parameters in a model. Wong and Zhou [28] defined green BIM as follows: “a model-based process for enhancing building energy-efficiency performance, and facilitating the accomplishment of established sustainability goals through generating and managing coordinated/consistent data during the entire lifecycle of projects”. With this definition, green BIM facilitates the analysis of building performance in terms of emissions, waste management, and construction methods [29].

With the rise of digital technologies and the use of BIM in the construction industry, there is also an increase in the use of BIM for improving the environmental impact of designs [9, [28]. In recent years, there have been numerous studies towards the use of BIM to perform LCA and different software applications have been developed [9, 10, 25, 26]. However, these studies mainly focus on the building design instead of infrastructure design. Liu et al. [12] observed that BIM in infrastructure is often used for design and construction management but not for sustainability purposes.

Antón and Díaz [30] described two approaches to integrate LCA and BIM. In the first approach, there is a direct connection between the BIM model and the LCA software. In this approach, the LCA software is able to use all information in the BIM model to complete the assessment. The second approach aims to include environmental properties in the BIM objects to enable designers to use this information in their decision-making process. While the interoperability between the BIM model and LCA software can be a major barrier in the first approach, the second approach can be less accurate depending on the used LCA methodology. However, everything considered, the second approach can be deemed as a good first step towards integrating LCA in the BIM model. This integrative approach helps present the environmental impact of a design on the same level as other design parameters. This allows designers to be more aware of the environmental impact that their decisions carry in the decision-making process [30].

Van Gemert [11] presented a BIM-based method to perform a LCA of a building. Based on an IFC export of a building model, the developed method was able to show the environmental impact of the design. However, this method is prone to human error because of the manual steps that are required to export the IFC file correctly. In this context, several studies have shown that for this reason there might be a preference for BIM-based LCA solutions that assess the environmental impact in real-time within the BIM model [7, 26]. An example of a BIM-LCA solution is the research by Bueno et al. [7] where an application was developed to automatically calculate the environmental impact of a building design. Using a combination of visual programming with Dynamo for Revit and Microsoft Excel, the environmental impact of the design was displayed graphically in Excel. The proposed method is based on ReCiPe 2008 [31] sustainability parameters that were added to the building objects in the BIM model. These parameters were used to calculate and visualize the environmental impact in Excel [7]. Similarly, Röck et al. used visual scripting (Dynamo for Revit) to visually display the embodied environmental impact of building elements in a conceptual model [32]. While they used a conceptual model of building with a very low Level of Detail (LOD), the study showed the potential of a visual representation of the embodied environmental impact.

Cavalliere et al. [10] presented another BIM-based LCA methodology. They facilitated LCA in the early design stages of building design by mixing different LCA databases. This approach ensured that reliable data is used even with a low LOD of the building design model.

Liu et al. [12] presented a theoretical framework that aims to build a bridge between BIM and rating systems in infrastructure design. The framework helps extract information from the BIM model, calculate the required values, and bring inputs from external sources, e.g., traffic information or climatological data.

There are a number of observations that can be made from this literature review: (1) Due to large information requirements and the need for an LCA expert, the LCA is often conducted at the end of the infrastructure design phase. This means that it is difficult to use the results in the decision-making process because decisions with the highest potential environmental impact are made early in the design; (2) Studies towards BIM-based LCA applications showed that interoperability between BIM- and LCA-software remains an issue. While there are export standards like IFC, there is still a chance of errors because of the numerous manual steps and the need for a sustainability expert. For these reasons, several studies described the need for a simplified and integrated approach where the BIM environment is used as the basis for LCA calculations and visualizations, without the need for additional experts and numerous manual steps. This approach allows the environmental impact to be evaluated in every phase of the design and therefore included in the decision-making process of designers; (3) There have been numerous studies that investigated the use of BIM for the integration of LCA in building design. Several frameworks and BIM-based LCA applications have been developed. However, studies on BIM-based LCA for infrastructure are uncommon. Moreover, the main issue that was identified is the complex nature of the LCA. This research tries to address this gap by proposing a framework for integrating the EIA in the BIM-based design of infrastructure projects.

3 Proposed framework

The proposed framework is based on the concept of automating and integrating the environmental impact assessment (EIA) in the BIM environment. As shown in Figure 1, the proposed framework consists of four sub-sections: (1) Data Collection, (2) Data Integration, (3) Environmental Impact Assessment and, (4) Visualization. In a nutshell, first the required information for the EIA is collected from the BIM model. After this, the data is structured in a systematic way that allows bidirectional data exchange between EIA database and BIM. Then, the environmental impact of each element in the project is assessed by finding the corresponding values in the EIA database and proportioning it based on the quantities of different materials used in each element. Finally, the relative score for the environmental impact of each element is evaluated and visualized in the BIM model using a heat map scheme.

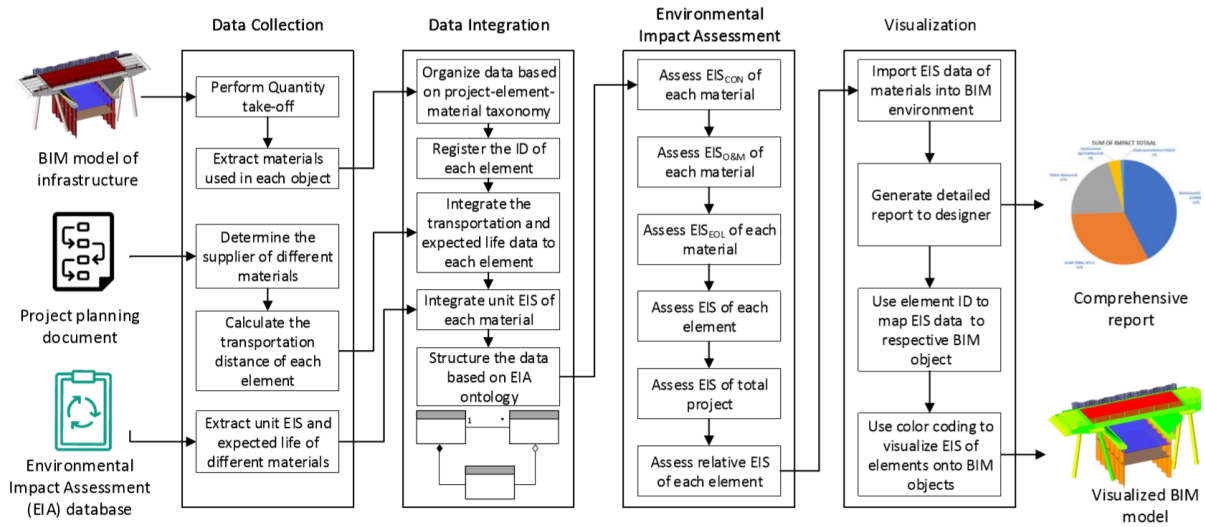


Figure 1: Proposed framework BIM-based Environmental Impact Assessment for Infrastructure

3.1 Data Collection

This phase aims to collect the required data to perform the BIM-based EIA. A BIM model contains rich semantics about every element in the project. In this sense, each element in the model is characterized, at the very least, by its object type (e.g., pile, slab, etc.), material (e.g., concrete, steel, etc.), and volume. However, conventionally, environmental impact is not included in BIM models as an attribute for different elements. On the other hand, EIA databases capture the environmental impact of different materials throughout their lifecycle.

To be able to incorporate the environmental impact of each element in the BIM model, first a comprehensive quantity take-off must be carried out to identify different materials used in different elements of the project. Next, the supplier of each material needs to be determined. This can be obtained from project planning documents. The information about the supplier is important because to measure the environmental impact of each material, the transportation distance of the material to the construction site needs to be known. This will be elaborated in Section 3.3. Finally, the required environmental properties to calculate the Environmental Impact Score (EIS) of each material are retrieved from EIA database. Table 2 shows an example of how construction materials are mapped in the environmental database [23]. This database contains environmental properties like Global Warming Potential (GWP) or Human Toxicity.

Table 2: Environmental properties example National Environmental Database [23]

Name base profile	SBK 844 Concrete Mortar C20/25 (i.e. 75% CEM III and 25% CEM I)
Unit base profile	kilograms
Abiotic depletion, non fuel	0.0000000901
Abiotic depletion, fuel	0.00027371
Global warming (GWP100)	0.086950528
Ozone layer depletion (ODP)	0.00000000352
Photochemical oxidation	0.0000225
Acidification	0.000238546
Eutrophication	0.0000526
Human toxicity	0.009386423
Fresh water aquatic ecotoxicity	0.000229498
Marine aquatic ecotoxicity	1.1262488
Terrestrial ecotoxicity	0.000169936
Total renewable energy	0.071583142
Total non renewable energy	0.61275881
Total Energy	0.68434195
Water, fresh water use	0.005530488
Waste, non hazardous	0.004809293
Waste, hazardous	0.043105809

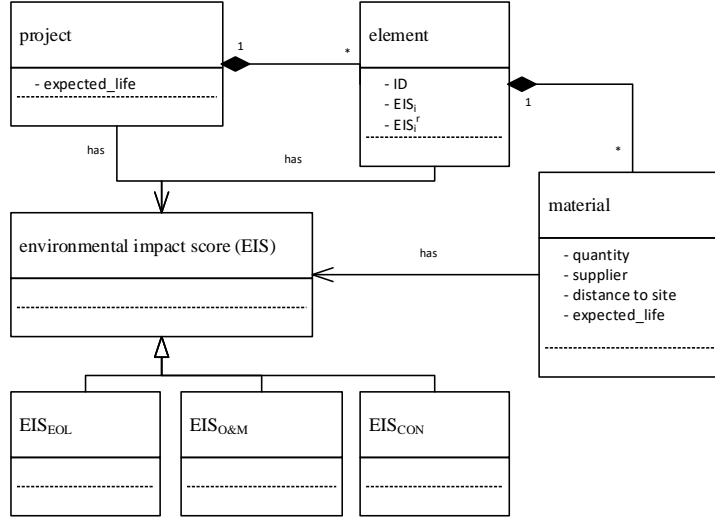
The environmental properties are translated into EIS by multiplying them with a price in €/Quantity [24]. This results in the EIS that consists of three different values, namely EIS of construction (i.e., EIS_{CON}), EIS of operation and maintenance (i.e., $EIS_{O\&M}$), and EIS of end of life (i.e., EIS_{EOL}). As the name suggests, each value represent the environmental impact of the material in a specific phase of the project. Table 3 shows an example of a material with its EISs.

Table 3: Example construction material with EISs

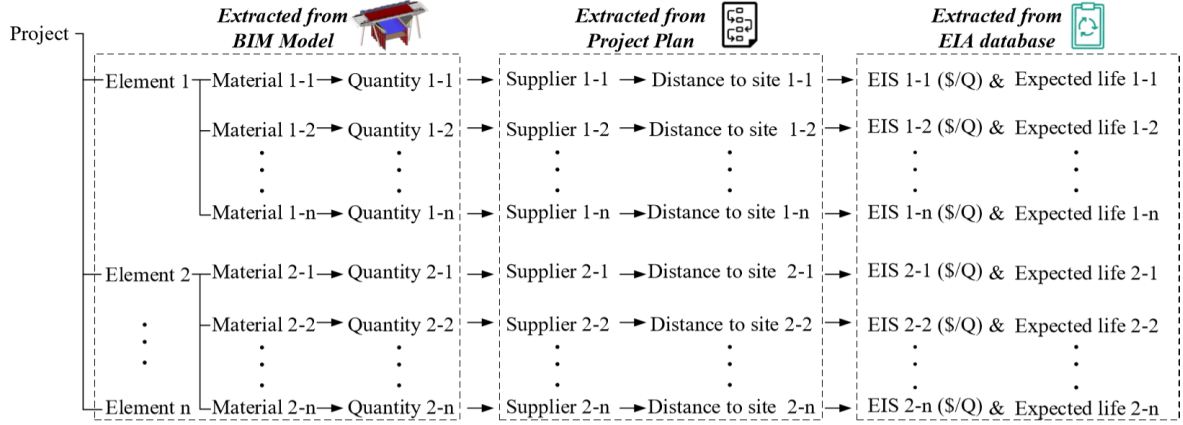
Material	Unit	Lifetime (years)	EIS_{CON} (€/Unit)	$EIS_{O\&M}$ (€/Unit)	EIS_{EOL} (€/Unit)	EIS_{Total} (€/Unit)
Concrete mortar C20/25 (CEMIII)	m3	100	29,48	0,00	3,21	32,69

3.2 Data Integration

To be able to further assess the environmental impact of the project, the collected data must be integrated and mapped in a structured way. Figure 2 represents the structure for the data integration and mapping. As shown in this figure, each project is decomposed into its constituent elements (e.g., columns, decks, etc.). It is important to retain the unique identifier (GUID) of each element from the BIM model because this GUID can later be used to map the EIS data back into the BIM model. It is also important to add relevant EIS attributes to BIM elements to accommodate the results of the EIS assessment in the BIM model, as will be explained in Section 3.4. Each element is characterized in terms of material(s) used in the element. The quantity of each material is extracted from the BIM model. From the planning documents, distance to the construction site can be calculated based on the information about the supplier of the material. When there is no supplier selected yet, an assumption can be made for the transportation distance. Finally, each material is associated with its unit EIS, which is extracted from EIA database. The unit EIS contains the different EISs and the expected life of the material.



(a)



(b)

Figure 2: (a) Data structure needed for BIM-LCA integration, and (b) mapping of the data for EIS assessment

3.3 Environmental Impact Assessment

Once the required data are gathered and structured as shown in Figure 2, the EIS of each material (EIS_j) can be assessed as shown in Equation 1. For this assessment, EIS_{CON} , $EIS_{O\&M}$, and EIS_{EOL} of each material are taken into account. Given that EIA databases present EIS of different materials in terms of unit cost per volume of the material, EIS needs to be multiplied by the quantity of the material. Additionally, the EIS_{CON} parameter includes the transportation distance to the construction site where the base value of EIS_{CON} is multiplied by the distance in kilometres. This distance can be adjusted in DuboCalc. It should also be highlighted that $EIS_{O\&M}$ depends on the expected life of the material. In case the expected life of the material (LT_m) is lower than the expected life of the project (LT_p), $EIS_{O\&M}$ needs to be multiplied by a factor representing the ratio of LT_p to LT_m to account for the replacement of the material, as shown in Equation 2. The EIS of an element (EIS_i), in turn, is the summation of EIS_j of different materials used in the element, as shown in Equation 3. Similarly, the EIS of the entire project (EIS_{total}) is the summation of all the EIS_i of different elements in the project, as shown in Equation 4. Equation 5 describes the relative environmental impact score of each element (EIS_i^r). Finally, Equation 6 describes the cumulative relative EIS of an element. This is the

combined relative EIS of a group of elements which have identical object types (e.g. the combined EIS of all steel sheet piles).

$$EIS_j = Q_j \times (EIS_{j,CON} + f_j \times EIS_{j,O\&M} + EIS_{j,EOL}) \quad \text{Eq. 1}$$

$$f_j = \begin{cases} 1 & LT_j \geq LT_p \\ \frac{LT_p}{LT_j} & LT_j < LT_p \end{cases} \quad \text{Eq. 2}$$

$$EIS_i = \sum_{j=1}^J EIS_j \quad \text{Eq. 3}$$

$$EIS_{total} = \sum_{i=1}^I EIS_i \quad \text{Eq. 4}$$

$$EIS_i^r = \frac{EIS_i}{EIS_{total}} \quad \text{Eq. 5}$$

$$EIS_i^c = \sum_{i=1}^I EIS_i^r \mid OT = identical \quad \text{Eq. 6}$$

Where:

EIS_j : environmental impact score of material j (€)

Q_j : quantity of the material j (m³ or ton)

$EIS_{j,CON}$: environmental impact score of material j in construction phase (€/Q)

f_j : life time factor representing the ratio of project life to the life of element j

LT_p : design life time of the project (years)

LT_j : design life time of the material j (years)

$EIS_{j,EOL}$: environmental impact score of material j at the end of life (€/Q)

$EIS_{j,O\&M}$: environmental impact score of material j in operation and maintenance phase

EIS_i : environmental impact score of element i (€)

J : Total number of materials in element i

EIS_{total} : environmental impact score of the total project (€)

I : Total number of elements in the project

EIS_i^r : relative environmental impact score of element i (€)

EIS_i^c : cumulative relative environmental impact score of element i (€)

OT : object type

3.4 Visualization

To facilitate an integrated approach towards the EIA in the design process of infrastructure projects, it is important to provide the designers with the right information. In the proposed method, two different types of information will be provided to the designer, namely the EIS report and visualized EIS in the BIM model.

In the EIS report, different types of materials used in the project are aggregated based on their type to indicate the contribution of each type of material to the overall environmental impact of the project. Designers can use this information to pinpoint the type of materials that account for high EIS and try to adopt different design strategies to reduce the use of these materials. Also, the report presents the absolute and relative EIS of each element. This information would allow

designers to identify which elements are more critical in terms of environmental impact and help them develop element-level strategies to improve the environmental score of the overall design.

As for the visualization of EIS on the BIM model, it is first necessary to add EIS_i and EIS_i^r of each element as attributes of each element in the BIM model. This is done through the mapping of EIS assessment data with the quantity take-off data using the unique element GUID. Once the EIS values are mapped to the corresponding attributes of the elements in the BIM model, a colour coding scheme can be used to visualize BIM model based on either the relative (EIS_i^r), absolute (EIS_i) or cumulative (EIS_i^c) values.

3.5 Workflow process

The proposed framework allows for transforming the workflow of the EIS assessment in the industry. As shown in Figure 3(a), in the current situation, there is a disconnect between the design and sustainability assessment. At the end of a design loop, the designer transfers the design to the sustainability department where the design is evaluated by the a sustainability expert. The sustainability expert synthesizes information from the designer and project manager to assess and analyse the EIS of the design. The result of this analysis is, then, communicated back to the designer who tries to develop strategies for improving EIS of the design. However, the design loop is already finished and design decisions with high environmental impacts are already made. Moreover, the analysis is normally presented to the designer in terms of graphs and tables, which would be difficult to link back to the elements in the model. The communication loop requires several rounds of back and forth data exchange, which introduce delays in the process. Also, as mentioned in the introduction, the process is not conducive to raising environmental insight in the designers as they are not able to immediately and visually observe the results of their design changes and strategies on the EIS of the construction.

The proposed framework, as shown in Figure 3(b) can change this process by automating the data exchange and the EIS assessment of the design. In the new process, the designers can immediately perform the EIS assessment at any points during the design phase. The proposed framework not only helps designers in identifying points of attention through the direct visualization of the EIS assessment on the model, but also it allows designers to perform rapid sensitivity analysis, through which they can observe the results of their design changes, no matter how minute, on the EIS performance of the construction. Given that designers can have an EIS assessment on isolated choices, it is hypothesized that, over time, designers can foster their sustainability awareness and insight by forming an understanding about the types of materials and design choices that significantly affect EIS performance of the design.

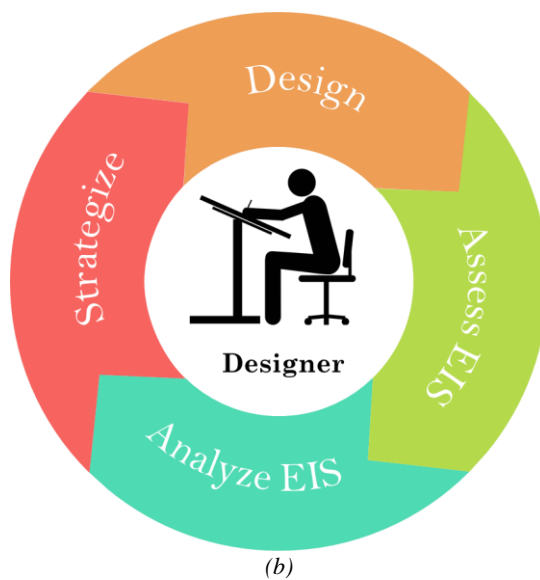
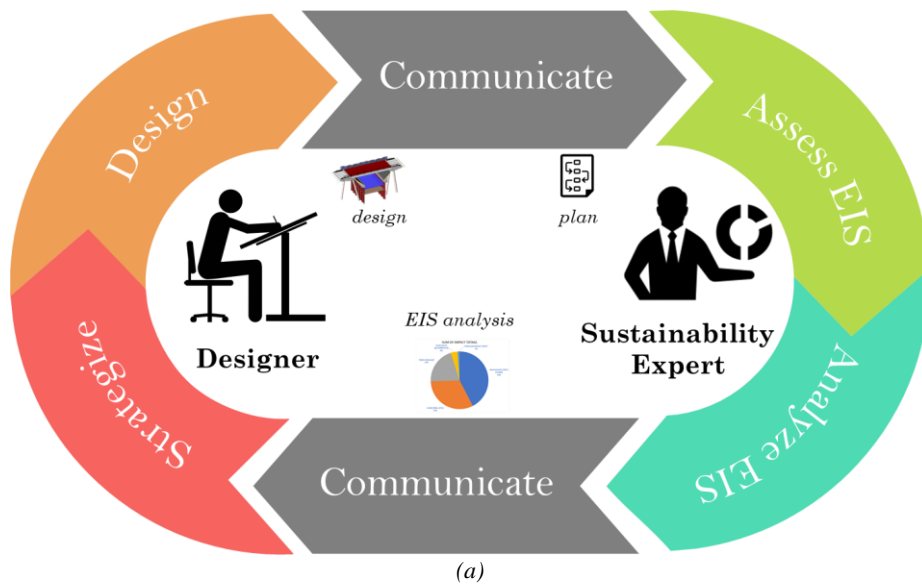


Figure 3: EIS assessment workflow based on (a) current fragmented approach, (b) proposed integrated approach

4 Implementation and Case study

To evaluate the proposed framework, a tool was developed as an application that integrates the EIS assessment in the design phase of infrastructure projects. As shown in Figure 4, the tool uses the BIM environment to retrieve model information, calculate EIS of the design, and present the results visually. Dynamo [33] is used to develop the tool as a plugin in Revit. Dynamo is a Python-based visual programming language that allows users to retrieve and modify information from a Revit model. To perform the EIS assessment, the Dutch National Environmental Database (NMD) [23] is used in combination with DuboCalc [22]. The structured quantity take-off data is generated by Dynamo and transmitted to an Excel sheet. Through a VBA script, quantity take-off, EIS values, and project management data are structured as shown in Figure 2. Then, through another macro in Excel, the EIS assessment is made based on the structured data and report is generated. EISs of different materials are then retrieved by Dynamo. Dynamo, then, adds EIS values as parameters and visualize the results in the model.

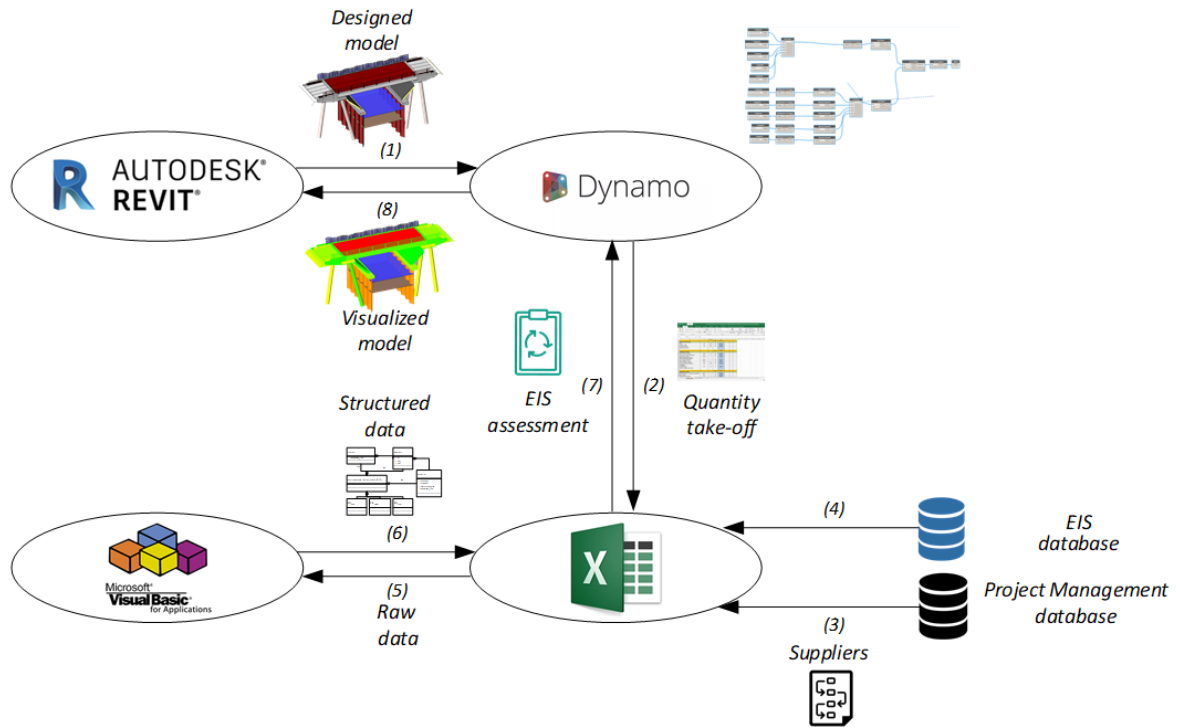


Figure 4: Architecture of the developed tool

The EIS database used in this study contains 70 different construction materials with their corresponding EIS. Table 4 shows a section of this EIS database. This aggregated list was composed by a sustainability expert using DuboCalc software [22]. DuboCalc translates environmental properties like Global Warming Potential (GWP) from the NMD into EIS that can be used in the EIS assessment as explained in section 3.3.

Table 4: Section EIS database

Unit EIS	Unit	Lifetime (years)	EISCON (€)	EISo&M (€)	EISeOL (€)
Asphalt (ZOAB)	ton	12	10,621	84,63	0,92
Asphalt (SMA, 0/11)	ton	16	10,372	59,28	0,92
Concrete mortar C20/25 (CEMIII)	m2	100	29,48	0,00	3,21
Concrete mortar C30/37 (CEMIII)	m3	100	15,14	0,00	6,34
Steel sheet pile	ton	100	96,43	0,00	-13,90
Composite sheet pile	ton	30	881,391	2168,32	47,89
Grout anchor	m3	100	28,345	0,00	1,12

4.1 Case study

The developed prototype is implemented and tested through a case study. The goal of the case study is to investigate the accuracy and calculation time of the developed tool in comparison to the manual EIS assessment. The case study is a infrastructure design project in the province of Utrecht, The Netherlands. The project comprises several concrete bridges, a highway and a large amount of steel sheet piles. Because of its large model size (~1800 elements), this project is well suited to investigate the calculation time of the prototype when it is employed on a large model.

To facilitate the calculation and presentation of the results, three shared parameters were added to the BIM model to display the absolute EIS (EIS_i), the relative EIS (EIS_i^r) and the unit EIS of each object. The parameters are named according to the NLRs (Dutch Revit Standard) to ensure coherence with the other parameters in the model.

Employing the developed tool on the case study allowed the EIS to be automatically calculated for each element within the model. The results of this automatic EIS assessment are presented within the model as parameter values, as shown in Figure 5.

Identity Data	
NLRS_WB_C_MKI_core	12.378775
NLRS_WB_C_MKI_item	Betonmortel C30/37 (CEMIII)
NLRS_WB_C_MKI_relative	0.002783

Figure 5: Shared parameters for the EIS, relative EIS and unit EIS in the BIM model

These parameter values are then used to create colour overrides in the BIM model as shown in Figure 6. The colour overrides can be based on the absolute EIS, the relative EIS or the cumulative relative EIS. The cumulative EIS combines the individual scores of identical object types, i.e. sheet piles, to create a more realistic presentation. The colours range from red (highest EIS) to green (lowest EIS). What can be observed from Figure 6 is that the road on the bridge contributes the most and also the sheet piles as a group have a relatively high contribution to the total EIS. A colour scheme like this allows the design team to quickly identify the high contributors to the EIS of the design and use this information in the decision-making process of infrastructure design projects.

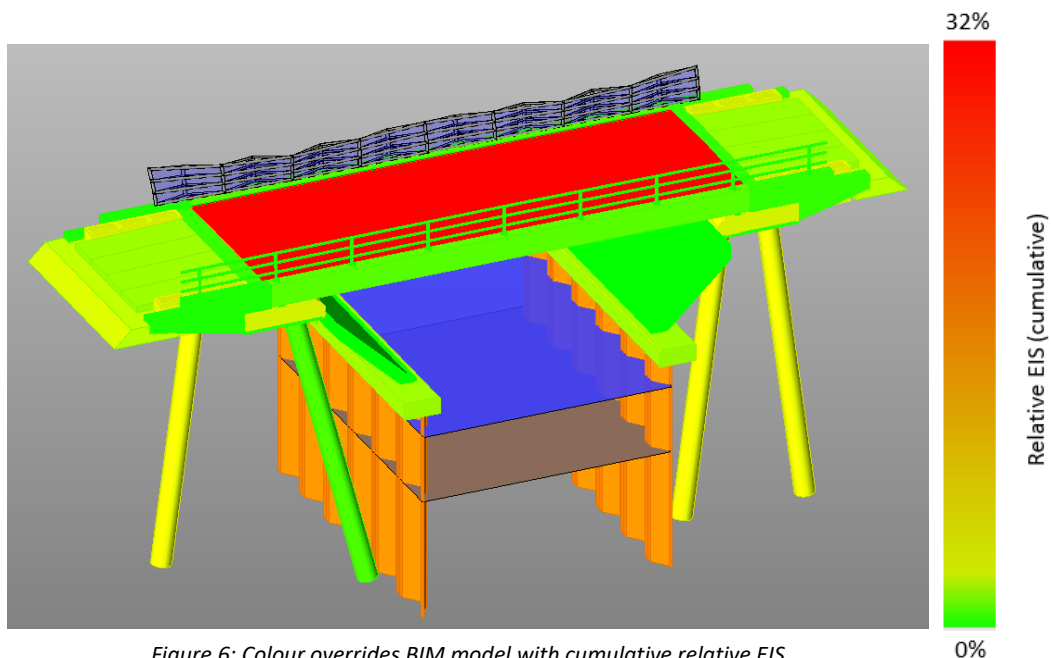


Figure 6: Colour overrides BIM model with cumulative relative EIS

Additionally, the raw data and more detailed information about the results are available in the Excel spreadsheet. Table 5 shows the results of five elements as they are presented in the Excel spreadsheet. It is important to note that the GUID of some elements (e.g. the GUIDs of the two elements of the bridge deck) is identical, this ensures that the total EIS of each object is calculated and displayed correctly.

Table 5: Example EIS calculation Excel spreadsheet

GUID	Object	Material	Quantity (m3)	Rebar (kg/m3)	Unit EIS	Adjusted quantity	Unit	EIS _i (€)	EIS _i ^r (%)
c0a55a80-daf1-41e6-afb6-cdd25c2b3e24-001265df	Bridge deck	Concrete	1635,29	150,00	Concrete Mortar C30/37	1635,29	m3	35.124	7,5
c0a55a80-daf1-41e6-afb6-cdd25c2b3e24-001265df	Bridge deck	Rebar Steel	245,29		Concrete Steel	245,29	ton	20.046	4,3
99d09524-fed3-4579-acb8-793e470e93c5-001616ee	Sheet pile	Steel	0,93	0,00	Steel Sheet pile	0,93	ton	77,1	0,0024
6d15c220-ecaf-4787-b2b0-a8200a6c54ec-00128cae	Grout anchor	Concrete	0,43	150	Concrete Mortar C30/37	0,43	m3	9,3	0,0003
6d15c220-ecaf-4787-b2b0-a8200a6c54ec-00128cae	Grout anchor	Rebar steel	0,06		Concrete Steel	0,06	ton	5,3	0,0002

Also, the results in the spreadsheet are presented in two other tables. One table presents the cumulative absolute and relative EISs of the object types, i.e., the EIS of all sheet piles combined. Another table presents the absolute and relative EISs of each material, i.e. Concrete Steel. Table 6 shows the three highest contributing object types to the total EIS of the case study and Table 7 shows the highest contributing materials.

Table 6: Cumulative EIS object types case study

Object type	EIS _i (€)	EIS _i ^r (%)
Sheet pile	117034	25
Road	68886	15
Bridge deck	55170	12

Table 7: Cumulative EIS material types case study

Material type	EIS _i (€)	EIS _i ^r (%)
Asphalt (SMA, 0/11)	181180	39
Concrete Mortar C30/37	99874	21
Rebar steel	41353	9

The cumulative EISs of the material types are also presented through a pie diagram as shown in Figure 7. This allows for easier interpretation of the results of the EIS assessment.

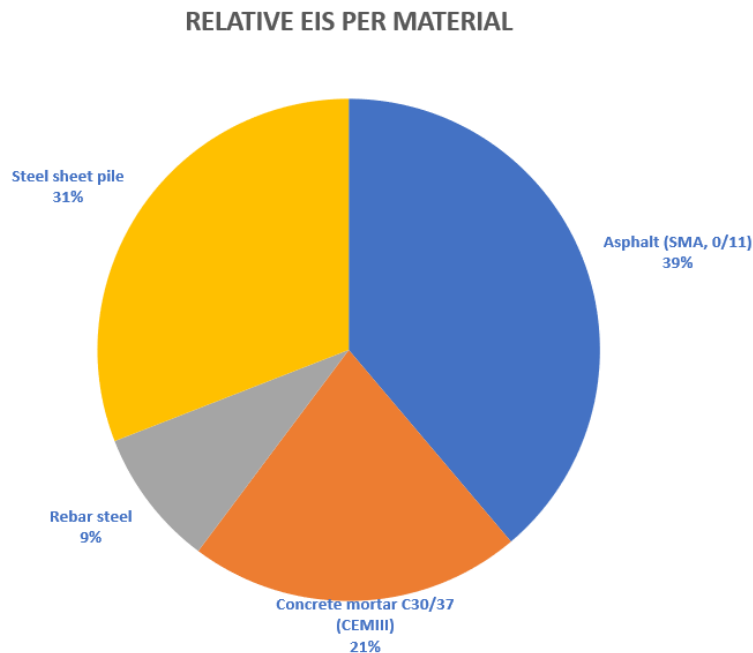


Figure 7: Pie diagram cumulative EIS per material

4.1.1 Tool accuracy and calculation speed

The performance of the tool is verified by comparing the results of the tool with the results of the manual EIS assessment. This ensures that the developed tool presents accurate results of the environmental impact of the design. Moreover, the calculation speed was analysed to see to which extent the EIS assessment is faster when employing the developed tool. It must be noted that element quantities of the manual calculation were adjusted to match the quantities inside the BIM model. This was necessary because of differences between the model quantities and the quantities used in the manual EIS calculations of the case study.

Table 8 shows a comparison of the manual EIS assessment and the EIS assessment of the developed tool. A number of elements was selected from the case study to investigate the accuracy of the tool. What can be observed is that the tool has an accuracy of 100% in almost all cases. There can be small, insignificant, differences as a consequence of rounding errors. Overall, the tool presents the same results as the manual process of the EIS assessment.

Table 8: EIS calculation accuracy

Model	EIS manual (€)	EIS tool (€)	Accuracy
Sheet piles	117.034	117.034	100%
Bridge deck	55.160	55.170	99,98%
Approach slabs	2873	2873	100%
Tubular piles	21.453	21.454	100%

Another goal of this study is to reduce the total cycle time of the EIS assessment of infrastructure design projects. To validate to what extent the developed tool achieved this goal, the calculation time of the EIS assessment was compared to the manual assessment. The manual process of the EIS assessment was aggregated to take between 1,5 to 3,5 days according to

experts within Witteveen+Bos. Table 9 shows the calculation time of the developed prototype compared to the manual assessment.

Table 9: EIS calculation speed analysis

Mode size (#objects)	Manual cycle time (days)	Calculation time prototype (min)
1800	1,5 - 3,5	35:00

Comparing the calculation times of the tool with the manual process shows an extreme time reduction. Where the traditional, highly fragmented, process takes several days, the tool is able to perform the EIS assessment of a design within minutes.

Finally, the developed tool was employed on another project to test the robustness of the tool. This project encompasses the design of a steel moveable bridge. Compared to the case study project, this project was relatively small (~230 model elements). However, the model characteristics (e.g. object types and materials) were different. Employing the developed tool on this project showed the same calculation accuracy of almost 100% as the case study project. Therefore, it is shown that the developed tool is able to perform an automated EIS on a wide variety of infrastructure projects.

4.2 Validation

The proposed framework and the developed tool have been validated through a workshop with experts from different fields of expertise within Witteveen+Bos. The goal of the workshop was to investigate to which extent experts perceive the usefulness of the tool. The expert panel consisted of a wide range of expertise, including infrastructure design, BIM coordination, sustainability, cost calculation, and project management. During the workshop, an introductory presentation was given about the development and the functionalities of tool. Next, the tool was demonstrated and experts could ask questions about the functionalities of the tool. Finally, the experts were asked to fill out a questionnaire which can be seen in Table 10. A total of 16 questions were divided over four categories: functionality/applicability, ease of use, scalability and sustainability consciousness. The scores ranged from 1 (Completely disagree) to 5 (Completely agree). Moreover, the experts all rated the developed tool in general with a score between 1 (bad) and 10 (good).

Table 10: Results expert panel questionnaire

Question	Score = 1 Count	Score = 2 Count	Score = 3 Count	Score = 4 Count	Score = 5 Count	Avg.
Functionality / Applicability						
[Q1] The current system helps effectively in evaluating the sustainability of a design	2	2	2	4		2,8
[Q2] The proposed method helps effectively in evaluating the sustainability of a design				3	7	4,7
[Q3] The current system helps effectively in improving the sustainability of a design	3	3	2	1	1	2,4
[Q4] The proposed method could help in improving the sustainability of a design			1	5	4	4,3
[Q5] The proposed method can easily be implemented in the workflows of design projects within the organization		1	1	7	1	3,8
Ease of use						
[Q6] The current system is easy to use	1	4	1			2,0
[Q7] The results of the current system are fast and easy to understand and interpret	1	4	1			2,0
[Q8] The proposed method is easy to use		3		6	1	3,5
[Q9] The results of the proposed method are fast and easy to interpret and understand		1	1	4	4	4,1
Scalability						
[Q10] The current system can easily be scaled up to be used in more design projects	2	2	2			2,0
[Q11] The current system could easily be adjusted to cover more (sustainability) aspects than just the EIS	1	4	1			2,0
[Q12] The proposed method can, without large changes, be used in other fields of expertise	1	1	1	5	2	3,6
[Q13] The proposed method makes it easier to include sustainability aspects in more projects within the organization				3	7	4,7
[Q14] The proposed method can easily be expanded to cover more (sustainability) aspects than just EIS				5	4	4,2
Sustainability consciousness						
[Q15] The current system fosters sustainability consciousness of designers	6	2		1	1	1,9
[Q16] The proposed method fosters sustainability consciousness of designers				6	4	4,4
Overall score						8,3

The results of the questionnaires can be translated into a spider diagram that is shown in Figure 10. This diagram presents a comparison between the performance of the current situation (orange) and the performance of the tool (blue). It is shown that the tool scores significantly higher on all four criteria compared to the current situation. This means that experts think that an application of the proposed framework is able to significantly improve the integration of environmental sustainability in infrastructure design. What can be observed from Table 10 and Figure 10 is that a strong majority agreed that the developed tool is a good method to evaluate and improve the environmental sustainability of infrastructure design (with average scores of 4,7 and 4,3). Especially compared to the current situation that is valued with a 2,8 and 2,4 respectively. During the workshop, experts identified that the developed tool has numerous potential applications within the infrastructure design process, i.e. evaluating design alternatives, optimizing designs, and presentation to clients. Similarly, the tool is easier to use and results are easier to interpret compared to the current situation (3,5 and 4,1 against 2,0 and 2,0). However, experts identify that a limitation of the tool is that there is still a need for a designer (with Revit and Dynamo experience) to perform the assessment. Moreover, experts agree that the tool makes it easier to incorporate environmental impact in the design process of infrastructure projects. Additionally, the developed tool fosters sustainability consciousness of designers significantly better than the current situation (with a score of 4,4 against 1,9).

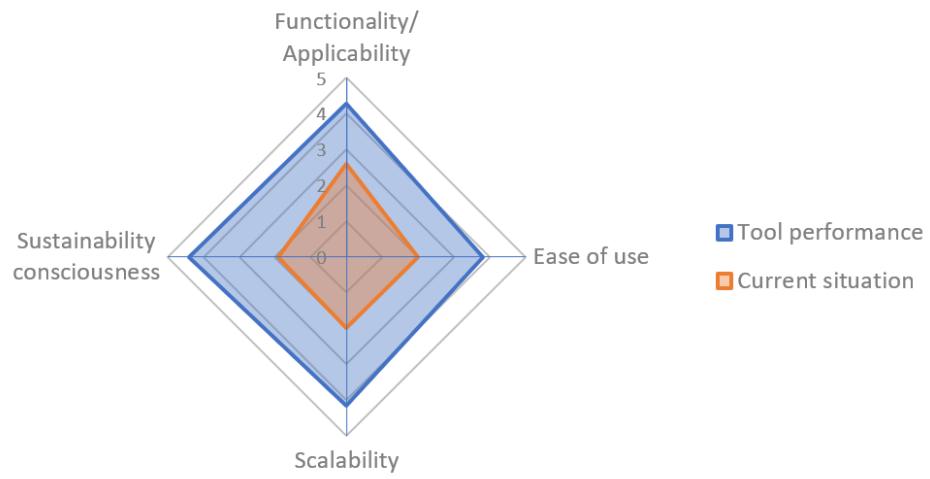


Figure 10: Tool performance comparison to current situation

5 Conclusion

With sustainability becoming more and more important for the construction industry, there is a need for sustainable infrastructure. However, a sustainability assessment is a complex process and an integrated approach to implement sustainable aspects in the infrastructure design decision-making process is currently lacking. This research presents a framework that aims to provide the designer with information about the environmental impact of a design to allow the design team to make design choices based on it. An application of the proposed framework was developed and tested on a case study to investigate the potential impact of the framework. The developed tool was presented to an expert panel which showed the great potential of an automated and integrated EIS assessment in infrastructure design.

From this study can be concluded that: (1) the proposed framework and its application have shown that the BIM environment is able to facilitate an automated and integrated EIA in infrastructure design projects; (2) it is shown that an accurate BIM-based EIA is much faster than the current, highly fragmented, EIA processes; (3) it is shown that a visual presentation of the EIS assessment results allows designers to easily pinpoint high contributing model elements to the total EIS and use this information in the decision-making process. Moreover, it is shown that a BIM-based approach fosters the sustainability consciousness of designers by showing them the environmental impact of their design choices.

There are a few limitations in this study; (1) there is still a need for a sustainability expert to create a project-specific EIS database because there is no direct connection to the environmental database; (2) the study only considers the environmental impact of construction materials. Other dimensions of sustainability, such as the social and economical dimensions, are not considered; (3) the developed prototype focused on the Dutch context by using the Dutch environmental database and Dutch standards. Its relevance to the international context could be further investigated; (4) The developed tool showed a concept of how the EIS assessment can be automated and integrated in the design process of infrastructure projects. This means that the developed tool might not be optimized in terms of performance and presentation.

Future research work on integrating sustainability aspects in the design process of infrastructure through BIM can be focused on: (1) calculating and presenting the environmental performance of an infrastructure design by means of multiple impact category indicators; (2) including more sustainability aspects such as social and economic pillars and the information required from the BIM model to achieve this; (3) developing a direct connection between BIM-software and the environmental database to further improve the integration of the platforms; (4) extending the applicability of the proposed framework to other geographical contexts.

6 References

- [1] P. Rode, R. Burdett, and J. C. Soares, “Buildings : investing in energy and resource efficiency Book section,” *United Nations Environ. Program.*, pp. 331–373, 2011.
- [2] J. P. Carvalho, L. Bragança, and R. Mateus, “Optimising building sustainability assessment using BIM,” *Autom. Constr.*, vol. 102, pp. 170–182, 2019.
- [3] N. Z. Abidin, “Sustainable Construction in Malaysia – Developers ’ Awareness,” *Proc. World Acad. Sci. Eng. Technol.*, vol. 5, no. 2, pp. 122–129, 2010.
- [4] ISO, “Environmental management: Life cycle assessment - Requirements and guidelines (ISO 14040),” Geneva, 2006.
- [5] I. Zabalza Bribián, A. Aranda Usón, and S. Scarpellini, “Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification,” *Build. Environ.*, vol. 44, no. 12, pp. 2510–2520, 2009.
- [6] J. Basbagill, F. Flager, M. Lepech, and M. Fischer, “Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts,” *Build. Environ.*, vol. 60, pp. 81–92, 2013.
- [7] C. Bueno, L. M. Pereira, and M. M. Fabricio, “Life cycle assessment and environmental-based choices at the early design stages: an application using building information modelling,” *Archit. Eng. Des. Manag.*, vol. 14, no. 5, pp. 332–346, 2018.
- [8] C. Bueno and M. M. Fabricio, “Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in,” *Autom. Constr.*, vol. 90, no. March, pp. 188–200, 2018.
- [9] A. Hollberg, G. Genova, and G. Habert, “Evaluation of BIM-based LCA results for building design,” *Autom. Constr.*, vol. 109, no. May 2019, p. 102972, 2020.
- [10] C. Cavalliere, A. Hollberg, G. R. Dell’Osso, and G. Habert, “Consistent BIM-led LCA during the entire building design process,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 323, p. 012099, 2019.
- [11] S. Van Gemert, “MPG-ENVIE: A BIM-based LCA application for embodied impact assessment during the early design stages,” no. May, 2019.
- [12] Y. Liu, S. Van Nederveen, C. Wu, and M. Hertogh, “Sustainable Infrastructure Design Framework through Integration of Rating Systems and Building Information Modeling,” *Adv. Civ. Eng.*, vol. 2018, 2018.
- [13] P. C. Bueno, J. M. Vassallo, and K. Cheung, “Sustainability Assessment of Transport Infrastructure Projects: A Review of Existing Tools and Methods,” *Transp. Rev.*, vol. 35, no. 5, pp. 622–649, 2015.
- [14] ASCE, “Policy statement 418 - The role of the civil engineer in sustainable development,” 2018. [Online]. Available: <https://www.asce.org/issues-and-advocacy/public-policy/policy-statement-418---the-role-of-the-civil-engineer-in-sustainable-development/>.
- [15] E. Meex, A. Hollberg, E. Knapen, L. Hildebrand, and G. Verbeeck, “Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design,” *Build. Environ.*, vol. 133, no. October 2017, pp. 228–236, 2018.

- [16] G. Finnveden *et al.*, “Recent developments in Life Cycle Assessment,” *J. Environ. Manage.*, vol. 91, no. 1, pp. 1–21, 2009.
- [17] U. Berardi, “Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings,” *Sustain. Dev.*, vol. 20, no. 6, pp. 411–424, 2012.
- [18] K. Griffiths, C. Boyle, and T. F. P. Henning, “Beyond the certification badge-How infrastructure sustainability rating tools impact on individual, organizational, and industry practice,” *Sustain.*, vol. 10, no. 4, 2018.
- [19] K. Griffiths and T. Henning, “Infrastructure sustainability rating tools – how they have developed and what we might expect to see in the future,” *Res. Gates*, no. June, 2015.
- [20] A. Amiril, A. H. Nawawi, R. Takim, and S. N. F. A. Latif, “Transportation Infrastructure Project Sustainability Factors and Performance,” *Procedia - Soc. Behav. Sci.*, vol. 153, pp. 90–98, Oct. 2014.
- [21] C. B. Kerry A. Griffiths, “Title : Comparative assessment of infrastructure sustainability rating tools,” no. April, 2017.
- [22] Rijkswaterstaat, “Dubocalc,” 2018. [Online]. Available: <https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/inkoopbeleid/duurzaam-inkopen/duurzaamheid-bij-contracten-en-aanbestedingen/dubocalc/index.aspx>. [Accessed: 03-Oct-2019].
- [23] Stichting Bouwkwiteit, “Nationale Milieudatabase,” 2019. [Online]. Available: <https://www.milieudatabase.nl/viewNMD/>. [Accessed: 25-Nov-2019].
- [24] A. K. Van Harmelen, R. H. J. Korenromp, T. N. Ligthart, S. M. H. Van Leeuwen, and R. N. Van Gijlswijk, *Toxiciteit heeft zin prijs: Schaduw prijzen voor (eco-)toxiciteit en uitputting van abiotische grondstoffen binnen Dubocalc*. 2004.
- [25] D. T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, and J. Tookey, “A critical comparison of green building rating systems,” *Build. Environ.*, vol. 123, pp. 243–260, 2017.
- [26] D. Bryde, M. Broquetas, and J. M. Volm, “The project benefits of Building Information Modelling (BIM),” *Int. J. Proj. Manag.*, vol. 31, no. 7, pp. 971–980, Oct. 2013.
- [27] B. Succar, “Building information modelling framework: A research and delivery foundation for industry stakeholders,” *Autom. Constr.*, vol. 18, no. 3, pp. 357–375, May 2009.
- [28] J. K. W. Wong and J. Zhou, “Enhancing environmental sustainability over building life cycles through green BIM: A review,” *Autom. Constr.*, vol. 57, pp. 156–165, Sep. 2015.
- [29] M. K. Ansah, X. Chen, H. Yang, L. Lu, and P. T. I. Lam, “A review and outlook for integrated BIM application in green building assessment,” *Sustain. Cities Soc.*, vol. 48, p. 101576, Jul. 2019.
- [30] L. Á. Antón and J. Díaz, “Integration of life cycle assessment in a BIM environment,” *Procedia Eng.*, pp. 26–32, 2014.
- [31] RIVM, “LCIA: the ReCiPe model,” 2011. [Online]. Available: <https://www.rivm.nl/en/life-cycle-assessment-lca/recipe>. [Accessed: 12-Nov-2019].
- [32] M. Röck, A. Hollberg, G. Habert, and A. Passer, “LCA and BIM: Visualization of

environmental potentials in building construction at early design stages,” *Build. Environ.*, vol. 140, no. April, pp. 153–161, 2018.

[33] Autodesk, “Revit.” Autodesk, 2019.