Implementation of a stochastic LCA method into BIM environment at infrastructure design projects - a case study of a bridge

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Date: 03/04/2023

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Preface

I hereby present my master thesis of 'Implementation of a stochastic LCA method into BIM environment at infrastructure design projects - a case study of a bridge'. This report describes the research that I have performed as the final part of my master's education in Civil Engineering and Management at the University of Twente. The research is conducted in collaboration with the Dutch company of Witteveen+Bos.

I have been working on this research and its adaptation in the past few months. I have obtained extensive knowledge of environmental impact assessment, design limitations and uncertainties at a preliminary design stage, and promising capabilities of the BIM design environment. Additionally, I have gained knowledge of parametric modeling, which was challenging and exciting at the same time. Lastly, I had the chance to get a glimpse of experiencing the practical side of civil engineering at Witteveen+Bos.

I thank my daily supervisors for quickly addressing my questions and helping with feedback throughout the research. Special thanks to Joao, who always provided encouraging comments next to critiques. This encouragement helped me move forward even in difficult times. Next, thanks to Farid for clarifying feedback and expectations each time to avoid confusion. Lastly, I want to thank Andree for timely replying to all my e-mails and meeting invitations and for accepting me and my thesis project even when we have not known each other beforehand.

Next, I would like to thank Farid and Maarten for the opportunity to work in collaboration with Witteveen+Bos. Also, I want to thank all my colleagues who contributed to my research through interviews, questionnaires, and workshops. Special thanks to the LCA department, who helped me with valuable insights, guided me, and raised questions. Their input significantly contributed to the precision of the environmental impact assessment part of the research. Additionally, thanks to all my colleagues who encouraged me every day in the office.

Lastly, I would like to thank my family and friends. Special thanks to my boyfriend, who helped me through difficult times and covered part of my education cost so I could finish. All help is highly appreciated and helped me achieve this milestone.

I hope you enjoy reading this report and hope it brings an exciting and innovative challenge to light for you with a potential application.

Gréti Péntek
April 2023, Almere

Summary

Purpose: The world is evolving towards a more sustainable future, which can also be observed in the infrastructure industry. More and more software and platforms are developed to account for the sustainability of a product during its entire life cycle. The sustainability consciousness is also becoming more influential in the construction industry; therefore, this research aims to develop a framework incorporating BIM-based Life Cycle Assessment with capturing the uncertainties involved in construction projects at an early design stage.

Methods: Therefore, the framework is developed based on an extensive literature review and an elaborate interview between experts in the related fields of sustainability, infrastructure design, engineering, and management at the Dutch company of Witteveen+Bos. The framework builds on various concepts of BIM-based LCA assessment, uncertainty assessment through stochastic methodologies, uncertainties involved in LCA, and a top-down approach to collect and organize all input parameters for the environmental impact assessment. The framework builds on the BIM environment with plug-in data sources that enhance information flow and limit interoperability issues. The framework aims to capture all potential scenarios and alternatives, and it generates a large number of outcomes. Hence, inherently considering uncertainty and sensitivity analysis that is inevitable in environmental impact assessments.

Results and discussion: The framework is developed and tested through a case study of a bridge project. The corresponding tool is developed in the BIM interface of Revit, and all the data collection, data integration, uncertainty handling, environmental impact calculations, and result generation are conducted via Dynamo. Furthermore, the case study considers a Dutch infrastructure project; therefore, the environmental impact assessment considers local construction costumes and builds on the project and data of the collaborating company of Witteveen+Bos. The results then show a more flexible way of calculating the environmental impact scores of a bridge asset and account for dynamic changes and uncertainties that could occur through the different phases of a construction project. Additionally, the results show 10.000+ outcomes per impact category per construction element with minimum and maximum possible outcome ranges. These ranges, coupled with graphs and visualizations, give a great insight into the improvement possibilities. However, the developed tool lacks built-in logical and structural integrity checks, which leads to unreasonably low environmental impact scores. At the same time, it considers economically disadvantageous solutions that result in overdesign and high environmental impact scores. Therefore, further development of the tool should be considered.

Conclusions: The developed framework can efficiently assess the environmental impacts of construction elements and provides informative ranges of outcomes, visualization, and graphs that help

users to make decisions based on sustainability insight at an early design stage. Furthermore, the framework incorporates all types of uncertainties that, with appropriate input resources, generate a more reliable environmental impact score estimation.

Abbreviations

BIM	Building Information Modelling
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme
ECI	Environmental Cost Indicator
EI_x	Environmental Impact of element ‘x’
EI_x^{EOL}	Environmental Impact of End of Life for element ‘x’
EI_x^{MC}	Environmental Impact of Manufacturing and Construction for Element x
EI_x^{O}	Environmental Impact of Operation for Element x
EIA	Environmental Impact Assessment
EPDs	Environmental Product Declarations
GUID	Globally Unique Identifier
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Engineering and Environmental Design
LOD	Level of Detail
MEAT	Most Economically Advantageous Tender
MKI	Milieukostenindicator
NMD	Dutch National Environmental Database

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1 Introduction

Current construction practices are consuming a significant amount of resources; for instance, buildings are responsible for 40% of energy use, 36% of greenhouse gas emissions, over 80% of raw material use, and at the same time, around 32% of the waste is produced by this industry in the European Union alone [1, 2]. To achieve a more sustainable construction industry, it is inevitable to modify the current approaches and philosophies. This new type of thinking must be implemented as early as the design phase as modifications at a later stage are quite time- and resource-intensive. Moreover, the goal of this new ideology should be to revise the linear economy (take-make-consume-dispose) to a more circular one (take-make-consume-end of life treatment) in order to reduce raw material consumption and reduce or eliminate waste production [3].

Dealing with more circular material use and reducing the environmental impact of infrastructure assets can be evaluated through Life Cycle Assessment (LCA studies). LCA, as specified by ISO14040, means that the product, process, or systems are evaluated based on their potential environmental impacts [4]. However, detailed information about the infrastructure asset is required to conduct an LCA, meaning that a detailed project design is needed. However, sustainability must be incorporated into the early design stage to significantly influence a construction asset's environmental impact. At this stage, however, various information about the final project is unavailable or not fully known. Therefore, an accurate LCA should be developed considering each unknown and uncertain parameter, which can be conducted through stochastic modeling principles [5]. Stochastic modeling tries to capture all potential outcomes of a given problem or scenario by considering random input variables, and it is built on different probability distributions [6]. Examples of stochastic methodologies are Monte Carlo Simulations, Markov-Chain models, regression models, Etc.

The significance of accounting for these uncertainties is emphasized by various writers [5, 7, 8]. Ivanov et al. [7] have pointed out the sources of uncertainties in their paper as they are naturally present in construction projects, from (1) including information available on material properties due to spatial and temporal variations to (2) the unavailable or insufficient information available about the construction asset, to (3) including all relations between all the attributes that are contributing to the overall life cycle score. It is important to note that these variabilities and their importance are pointed out as early as 1995 [5], and the evaluation of uncertainties and the endeavor to incorporate them into the LCA studies have exponentially increased since then. As an example, Baker and Lepech [8] found in their work that different electricity mix usage in the USA, during the operation phase of an asset, can result in as significant as around 35% to 50% of the total life cycle's global warming potential (GWP), meaning that a few seemingly insignificant stochastic aspects can change the final LCA result entirely. Therefore, it is clear that quantification and implementation of uncertainties in the product's life cycle are crucial.

One of the commonly used design tools for construction projects nowadays is Building Information Modelling (BIM), which could potentially be used to assess LCA in the early design stages of a project. Additionally, a new tool or framework could be developed to incorporate LCA assessment in early design stages with approximate stochastic distributions to account for uncertainties. In recent years, more and more research has been conducted in the fields of stochastic LCA, BIM-based LCA, and the incorporation of uncertainties and dynamically changing variabilities in construction projects. However, these areas of knowledge development are still fragmented from each other. For example, Hanbury and Vasquez [9], Miller et al. [10], Baldoni et al. [11], and Barahmand and Eikeland [12] focus on incorporating uncertainties in a specific context (e.g., geothermal energy, renovation projects, Etc.) and evaluate and develop various types of stochastic methodologies that appropriately accommodate uncertainties; others like Santos et al. [13], Lee et al. [14], and Meex et al. [15] are focusing on the integration of BIM and LCA; while others are emphasizing the importance and sources of uncertainties in LCA like Igos et al. [16] Baker and Lepech [8], Feng et al. [17]. Hollberg et al. focus on more than one area of the research field of BIM-based LCA and incorporating stochasticity in LCA; however, they are dealing with them separately in various research papers [15, 18, 19]. Therefore, incorporating all these research areas into one study and framework could be promising for the construction industry in developing a more sustainable future.

Additionally, there is great potential in developing a stochastic LCA in a BIM-based environment to help both develop a sustainable design and apply for permits, potentially saving time, money, and effort to execute and develop the design, the LCA, and permit obligations separately [19]. Several examples can be given to emphasize this framework’s applicability and potential use.

Firstly, since 2015 public authorities in the Netherlands must implement a fully sustainable procurement [20]. Therefore, it is necessary to include quality input in the procurement process to ensure innovative and high-quality solutions. Among other aspects, such as a public-oriented approach, project management, design, and risk assessment, tendering bids should also include sustainability aspects. Then, the tendering is decided based on the most economically advantageous tender (MEAT) [20]. As an example, Rijkswaterstaat, the most significant public client in the Netherlands, often asks for an environmental impact assessment to be part of the submitted tender bid [20]. Then all the tender bids are compared with the environmental impacts included, meaning a competitive environmental impact score should be achieved to win the project. Additionally, the submitted environmental impact score should be beneath the maximum target value; otherwise, the bid will be excluded from the tender, which is financially undesirable for the contractor. Moreover, accounting for uncertainties in LCA on the tendering process is crucial to provide reliable environmental impact scores and to eliminate the need for assumptions and guessings regarding unknown details of the construction project. Additionally, incorporating uncertainties in the tendering process highlights problematic issues and reduces unforeseeable problems in the future. Therefore, contractors should consider and execute a serious environmental impact assessment (EIA) at the early design to ensure that the EIA score is within the maximum target value, represents reliable environmental impact scores, and is competitive with other contractors' EIA scores.

In addition to the idea mentioned earlier, the contractor that executes the project must demonstrate that the final product remains within the required environmental impact value during the design and construction phases. To ensure the project is on track, Rijkswaterstaat periodically asks for updated reports of the environmental impact score regarding soon-to-be-constructed elements [20]. At this stage, the project has a high degree of detail, and design changes are expensive to be implemented. Accordingly, the contractor would like to ensure that it could provide an EIA score at any project stage within a reasonable time and that the EIA score in his bid is not exceeded. Moreover, with a stochastic framework, the contractor could predict a more reliable range as different uncertainties are included in its calculations.

As is implied, producing a reliable environmental impact score within a short time is essential. The problem with determining such a score for tendering processes is that it takes a significant amount of time. Executing an LCA for an infrastructure project would mean that even a small asset consists of over a hundred components. These components could be made from different manufacturing processes, and materials, they need different transportation, energy, and water needs, and their demolition potentials also vary. However, all this information is required, and collecting this information at an early design stage is problematic and even more time-consuming due to all the uncertainty aspects, thus, assumptions involved. Therefore, the framework must operate fast to effectively determine the environmental impact score, make design changes, recalculate, and repeat this iterative process in a timely manner.

Lastly, stochastic environmental impact assessment within a BIM environment could effectively highlight potential risks and possibilities in identifying the elements with the highest impact scores at the beginning and investigating the uncertainties related to these components and the corresponding construction processes, transportation, Etc. When a great range of uncertainty is identified for an element (great risk) and has a significant influence on the overall EIA score, this element should be investigated in more detail to narrow down the uncertainties related to it and even make preliminary decisions to ensure that the future EIA score remains within the required range.

Based on the limitations and potential benefits mentioned above, this research aims to develop a BIM-based Environmental Impact Assessment (EIA) framework that integrates the fragmented research fields of (1) uncertainties involved in LCA, (2) the BIM-based LCA, and (3) different stochastic approaches to account for uncertainties in an organized manner for infrastructure assets to (i) evaluate the environmental impacts of an infrastructure asset, (ii) to enable two-directional data exchange between BIM and LCA software, (iii) to provide immediate feedback to users about their design choices quickly, and to (iv) provide a reliable environmental impact range at an early design stage.

Based on the objectives mentioned above, the following main research question is formulated: *How could uncertainty through a stochastic methodology and LCA process be incorporated into a BIM-based environment impact assessment to effectively improve the design process of an infrastructure construction project at an early design phase?*

The research report is structured in the following sections. Firstly, a detailed literature review is presented to summarise the current state-of-the-art considering sustainability and life cycle assessment in the construction industry with its stochastic nature, and BIM-based LCA approaches in section 2. Secondly, the methodology is presented in section 3, the proposed framework of the BIM-based stochastic LCA is explained in section 4, then, in section 5, the framework is implemented and tested with a case study. Lastly, the results, discussion, and conclusion are presented, in which the most critical findings, limitations, and future research possibilities are discussed.

2 Literature review

The research builds upon three main fields of (1) sustainability in the construction industry, (2) uncertainties and stochastic LCA applications, and (3) the utilization of Life Cycle Assessment in Building Information Modeling, specifically in infrastructure design. To discuss the basis of this research and to successfully develop a BIM-based stochastic framework, each of these fields is described with basic definitions and current knowledge about them in the following sub-sections. Note that definitions and basic explanations from literature are emphasized with Italic letters, and some of the above-mentioned main fields are described further in depth with sub-topics. Then identified methods are summarized and evaluated to investigate their applicability in this research context.

2.1 Sustainability in the construction industry

The awareness of sustainability emerged in the 1970s, and since then, the application of the ideology has increased in various industries [21]. Nowadays, sustainability is more and more considered in the construction industry in line with the Sustainable Development Goals (SDGs 9) [22]. Over the years, different definitions of sustainability have been proposed. Still, Brundtland defined sustainable development first in 1987 as "*the ability to meet the needs of all people in the present without compromising the ability of future generations to meet their own*" [23]. Sustainability has three environmental, economic, and social pillars that are considered throughout the product, process, or system's life cycle [24]. Each of these pillars is equally important in developing towards a sustainable future; however, the environmental aspect is the most often investigated among industries and companies [25]. The construction industry is not an exception to this idea either. Nevertheless, it is reasonable to investigate the environmental impact of construction assets as they are responsible for great raw material use, energy use, and waste production leading to an outstanding environmental impact among industries. The construction industry's environmental impact can be assessed through Life Cycle Assessment (LCA), as this methodology can quantify the environmental impacts of construction assets [15].

2.2 Life cycle assessment in the construction industry

In general, an LCA study is often complex, time-consuming, and requires detailed information about the project [4]. Therefore, it is usually executed at the end of the detailed design phase, when all the necessary data and information are available. This means that each material choice, the supply chain steps, the operation phase, and sometimes even the end-of-life treatment of the asset is known. Nevertheless, even if a high level of design detail (LOD 400 or 500, for instance) is investigated, various aspects and conditions are still assumed based on "expert judgment" [5] as the life cycle of a product could last for a significant time period. As an example for bridge assets, these studies consider a fixed life cycle of the asset as a few years for the design and construction of the infrastructure, then 50 to 100 years for the operation phase, and a few years in the end for the end-of-life treatment. Considering 50+ years of the life cycle of a product in today's rapidly developing society, it can be safely stated that changes in the calculation will occur both during construction, operation, and end-of-life project stages [26, 27].

LCA defines and quantifies the potential environmental impacts of a product, process, or system along its lifecycle, starting from raw material extraction through production, installation, and operation to the end-of-life (EOL) or demolition phase [4, 28]. As described by ISO 14040 [4], an LCA comprises four main steps: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. However, the execution of LCA in the construction industry is often done using predefined datasets describing commonly used materials and components with their raw material needs, supply chain aspects, and production processes. This information is also formulated in the product's Environmental Product Declarations (EPDs), which suppliers recently provided due to customer demands and expectations [29]. Consequently, the inventory (LCI) and impact assessment (LCIA) phases of the LCA are often merged into one step by multiplying the material quantities with the pre-determined characterization factors from the database [30].

LCA applications in the construction industry increased significantly in the last two decades [31], and numerous rating systems have been developed to assess the environmental impact of construction projects [29]. Some of these rating systems, namely, are the Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom and Leadership in Engineering and Environmental Design (LEED) in the USA [29]. However, these rating systems are developed for building design and are rarely considered for infrastructure projects [32]. Nevertheless, this aspect is misleading as infrastructure-related projects account for a great deal of raw material and energy use and waste production [33].

Realizing the abovementioned issue in the early 2000s, the Institute of Civil Engineers developed a determinative rating system for infrastructure assets in the United Kingdom called Civil Engineering Environmental Quality Assessment and Awards Scheme (CEEQUAL) [34]. This rating system aimed to provide an approved sustainability assessment for civil engineering, including different infrastructure assets, landscaping, and civil works in public spaces [35]. CEEQUAL became an integral part of the construction industry in the UK and provides environmental and social indicators to assess the sustainability of infrastructure assets. Since November 2015, CEEQUAL has been part of the Building Research Establishment (BRE), and in collaboration with BREEAM, they became one of the most prominent standards and certification tools for the built environment in the UK, and it is acknowledged around the world [35].

Nevertheless, each country uses different LCA tools to accommodate its environmental goals and ecosystem characteristics [36]. The commonly used LCA tools in the Netherlands are SimaPro and DuboCalc [37]. SimaPro is a LCA tool developed based on 30 years of sustainability principles and contributes to policy development. The analysis carried out within SimaPro can comply with ISO standards and is applicable for generating EPDs and reports [38]. On the other hand, DuboCalc is a sustainable calculation software tool developed by Rijkswaterstaat that calculates the environmental impact of soil works, road, and water constructions along the asset's life cycle and gives the environmental impact score (in Dutch MKI) in terms of euros [39]. Additionally, this tool uses the Dutch National Environmental Database (NMD), which contains the environmental impact of locally used construction materials. Using one or more external databases within the LCA tool is a common approach and provides a more elaborate, potentially more precise environmental impact assessment process within a region or even around the world [40].

Numerous LCA tools are available, and their performance and efficiency are compared by various studies summarized by Rodriguez et al. [41]. However, according to the nature of the LCA studies, they are often limited to their specific goal and scope definition, to the database and the impact assessment method they use, and they are often sensitive to the input data [41]. Moreover, variations could also occur due to the knowledge of the person who executes the assessment [19]. This implies that LCA studies are highly dependent on uncertain aspects, and the same assessment could result in different outcomes just by considering the different tools, methods, and assumptions made along the process.

2.3 Uncertainties and stochastic LCA application in the construction industry

2.3.1 Uncertainty in the construction industry

Uncertainty along a construction project and process is inherent, always present, and should not be ignored. Considering and incorporating these uncertainties are necessary to increase the reliability and credibility of the LCA score of an asset [16]. Uncertainties can be originated from six reasons: parameter uncertainty, model uncertainty, uncertainty due to design choices, temporal and spatial variability, and variability between different data resources [5, 16]. From a different perspective, Ivanov et al. [7] identify two types of uncertainties: aleatory and epistemic uncertainties. The first refers to the natural randomness of events and processes in the real world, which are unforeseeable and cannot be calculated; thus, they cannot be eliminated or excluded. The latter is associated with the lack of data or information, which can be reduced. As a result, epistemic uncertainties could be defined by probabilistic distributions to increase the precision of a LCA study. Other studies identify different categories of uncertainties. For instance, May and Brennan [42] suggest numerical and qualitative uncertainties, while Huijbregts et al. [43] and Hong et al. [44] propose scenario or assumption uncertainties, parameter uncertainties, and model uncertainties. Bamber et al. [45] describe parameter uncertainty as the uncertainty in data quality. These uncertainties are present in all the incorporated data, meaning all the data that is needed for the environmental impact calculations, including but not exclusive to the material type, its quantity and quality, the supplier data, the transportation distance, mode, and the number of trips between locations, the utility used, waste produced, the LCA data, Etc. Furthermore, the parameter uncertainty tries to capture the variability in data reliability, the completeness of the available data, the temporal and geographical correlation, and the technological alternation. Next, the scenario-related uncertainty also called uncertainty related to the choice, relates to all the choices made in the LCA process's goal and scope definition, meaning the selected system boundary, the allocation method, the functional unit, Etc., and the model uncertainty refers to the logic of the model itself.

Nevertheless, each classification method aims to categorize the uncertainty involved in the project to reduce their significance to the largest extent possible. The identified uncertainty categories, their content, and assessment methods are collected in Table 1.

Table 1 - Classification and assessment methods of uncertainties in LCA (Adapted from Zhang and Wang [46])

Reference	Classification	Content	Assessment method
Igos et al. **[16]** and Pian et al. **[5]**	• Parameter uncertainty	Lack of data, non-representativeness, empirical inaccuracy	Qualitative and quantitative assessment
	• Model uncertainty	Assumption on programming	
	• Uncertainty of choices	The functional unit, allocation procedure	
	• Spatial variability	Spatial characteristics of data	
	• Temporal variability	Temporal characteristics of data	
	• Technology variable	Inherent differences among technologies	
Ivanov et al. **[7]**	• Aleatory uncertainty	Natural randomness of events	Qualitative and quantitative assessment
	• Epistemic uncertainty	Lack of data or information	
May and Brennan **[42]**	• Numerical uncertainty	-	Probabilistic models and quantitative methods
	• Qualitative uncertainty	-	Assessed scores representing data quality
	• Scenario/assumption uncertainty	System boundary, functional unit, the allocation method	Scenario analysis

Huijbregts et al. **[43],** Hong et al. **[44],** and Bamber et al. **[45]**	• Parameter uncertainty	Material and energy flow, other input data	Numerical and empirical methods, e.g., Monte Carlo simulation
	• Model uncertainty	Transformation factor, process modeling	Probabilistic method, sensitivity analysis

Moreover, Zang and Wang [46] propose a '*data quality pedigree matrix*' that incorporates uncertainties related to the data source, reliability, and spatial, temporal, and technical correlations. The pedigree matrix adapts a five-degree grading system spreading from completely unknown data (low data quality with score 1) to fully known and factual data (high data quality with score 5). The description of each level at the data quality pedigree matrix is presented in Table 2. Later Zang and Wang [46] quantified the described variables in their pedigree matrix. The quantified values describe uncertainties spread between 0 and 1, where 0 refers to no uncertainty present, and 1 refers to complete uncertainty.

Table 2 - Data quality pedigree matrix adapted from Zang and Wang [46]

Data quality score	Data quality indicator				
	Data source	Data reliability	Temporal correlation	Spatial correlation	Technological correlation
1	Unknown	Nonqualified data or unknown	Data from more than 15 years ago	International data or unknown	Data from related processes with different technology
2	Unverified data from irrelevant enterprises	Estimated data based entirely on assumptions	Data from between 10 and 15 years ago	National data	Data for related processes with similar technology
3	Unverified data from relevant research groups	Calculated data partially based on assumptions	Data from between 6 to 10 years ago	Regional data	Data from the studied process and enterprise with different technology
4	Verified data from interested enterprises	Calculated data based on measurements	Data from between 3 to 6 years ago	An area with similar conditions	Data from the studied process and technology of other enterprises
5	Verified data from an independent source	Directly measured data	Data from within the last 3 years	Field data	Data from the studied process, technology, and enterprise

Additionally, Igos et al. [16] identified three levels to assess uncertainties, namely, (1) the basic level, which requires low effort within an LCA software and is based on minimum and maximum values, (2) the intermediate level requires significant effort still within an LCA software and is based on probability distributions, and (3) advanced level which needs significant effort in a programming platform (as LCA software are not capable of that degree of complexity) and it is based on correlations and statistical tests. Unfortunately, traditional LCA tools are not sufficiently robust yet to model the complex, dynamic, and emerging nature of the construction industry; therefore, the development of an accurate advanced level of stochastic LCA tool is limited [10].

To overcome uncertainty-related issues, Igos et al. [16] suggest a step-by-step scheme that could be followed starting with (1) qualitative and quantitative characterization of uncertainties from the model and inputs, to (2) uncertainty analysis that reflects in the output, to (3) sensitivity analysis to investigate the influence of input uncertainty on the result, and (4) the communication of the uncertainty to the public. Following these steps, a suitable method can be selected to deal with the uncertainties. Feng et al. [17] suggest eight uncertainty methods and variants. Four of these are the most often used ones: the Monte Carlo simulation, sensitivity analysis, pedigree matrix within data quality indicators, and fuzzy-related methods.

2.3.2 Stochastic LCA in the construction industry

As mentioned earlier, the appraisal of uncertainties in LCA in the construction industry was first emphasized in 1995. Since then, various studies have tried to capture uncertainties and stochasticity with probabilistic distributions, the Monte-Carlo method [19, 47, 48], Bayesian probabilities [10], Markov Chain modeling [49], or similar. For instance, Miller et al. [10] developed an emerging system framework implementing Bayesian probabilities within an Agent-Based model context to gain insight into probable trends and to develop a deeper understanding of potential LCA results of different construction design alternatives. Within this study, a more advanced approach has been investigated to develop simulation models, such as scenario or Agent-Based simulations (ABS) [10]. However, the limitation of developing such a model could be the lack of data and robustness for the basis of the analysis. From a different perspective, Hollberg et al. [19] suggested implementing a generative model concept to generate and evaluate different design alternatives automatically. As it can be observed from the examples, simulations are often conducted nowadays in the construction field too [50], as they can evaluate different scenarios and possibilities swiftly, thus, saving time and resources. However, they can get complicated very quickly [50, 51].

Currently, uncertainties are considered mainly for the inventory assessment of the LCA study, and variations are represented in the impact assessment calculations [10]. The same idea is captured by Hollberg et al. [19], who simplified the LCA concept into three steps of input-calculations-output, where uncertainties occur in the input (inventory), then they are reflected in the calculations (impact assessment), which then resulted in different outcomes. Moreover, they suggest implementing a safety factor of 1,25 to add a surcharge for uncertainty to account for any unforeseeable changes.

Nevertheless, a crucial point to raise is that recent studies try to incorporate uncertainties in the LCA calculations and develop different stochastic LCA frameworks to close this gap; however, they are focusing only on a small part of the construction process or project. For example, they focus solely on material choice and embodied CO_2 emission [46, 49, 52], energy and transportation [9], greenhouse gas emission [49], Etc. Thus, these studies often overlook the interconnectedness of the different aspects, and the holistic view is also missing. For example, only focusing on the stochastic nature of material choice at an early design stage would disregard the corresponding construction, transportation, installation, and energy needs. Nevertheless, some of these studies achieve remarkably elaborate frameworks using the above-mentioned probabilistic methods and techniques.

Nowadays, there are a few commercial LCA software that can be used to account for uncertainties, for example, GaBi software by Sphera, openLCA, and SimaPro. However, it must be noted that in most cases, the programs are limited to one or two stages of the LCA assessment, e.g., stochastic attributes only present in goal and scope definition, inventory analyses, or impact assessment; and for a few aspects only, e.g., stochasticity in material choices or focus on CO_2 emission [5]. Additionally, these LCA tools require previous knowledge to use them correctly. However, Hollberg et al. [19] investigated and concluded that architects and engineers involved in the early design phase are usually not experienced with sustainability and LCA, and experts in the LCA field are only involved at a later stage. However, this mismatch leads to limitations in investigating design choices from a sustainability perspective in the early design phases.

2.4 Life Cycle Assessment and Building Information Modelling

2.4.1 Building Information Modelling

In recent years, Building Information Modelling (BIM) has gained significant popularity in the construction industry. The idea behind developing this environment was to create a platform where multidisciplinary data is structured in a digital representation of an asset across its lifecycle [53]. There is a number of acknowledged dimensions within the BIM concept, such as 3D for visual 3-dimensional design, 4D for the integration of planning and scheduling, 5D for costs of elements, 6D, and 7D for energy analyses and facilities management [54]. These layers add information to the project, and due to their centralized operation, each party can access up-to-date information at all times. With the potential to add all kinds of information to the BIM environment, it is promising because it could also facilitate the addition of a stochastic LCA framework. Charef [54] suggests that LCA could be added to BIM as the eighth dimension.

2.4.2 BIM-based LCA applications in the construction industry

With today's rapidly evolving technology, the increase in the complexity of modern construction projects, and the desire to assess the environmental impacts of infrastructure assets require a well-functioning interdisciplinary design tool such as BIM [55]. There is growing attention to developing a more efficient and sustainable design methodology that integrates BIM and LCA approaches, also known as “Green BIM” [56]. The BIM modeling approach is important in sustainable infrastructure design as it provides transparency and clarity in every design stage. It is an efficient design process tool and could account for energy and water usage and waste products along the asset's life cycle [57]. In recent years, there has been an increasing number of research conducted about BIM-based LCA frameworks [18, 58, 59]; however, most of these frameworks deal with building design rather than infrastructure design. Along with similar methodologies to the building design concepts, this gap should be possible to fill for infrastructure projects too.

Santos et al. [13] have identified three approaches to integrate LCA with the BIM environment. The first one is a fragmented method that utilizes several programs to conduct the LCA analyses; the second builds upon the use of a quantity take-off from a BIM model to use it as the basis of the LCA assessment; and the third one suggests including the LCA information about materials and components within the BIM interface. The latter two are the commonly used ones as they are semi-automized; however, each has drawbacks. The second approach has great detail and accuracy; however, the interoperability between LCA and BIM software can be a barrier. The third approach would be great for designers as detailed information is available within the design interface; however, the LCA capability of this approach is limited to material choices and simplified calculation [60]. Even though Santos et al. [13] emphasize the importance of utilizing the BIM interface to its full potential and including LCA information within the BIM environment, they encountered a number of issues related to this approach of simplified LCA assessment, lack of straight connection between elements and manufacturers, missing information about potential transportation and installation processes, and the limitation to include different type of environmental impacts.

Genova [61] shares the same insight with Santos et al. [13] but groups the BIM-based LCA methodologies into conventional, static, and dynamic approaches. The conventional approach refers to the execution of LCA calculations separately from the design environment, the static approach is a one-directional approach using the quantity take-off list as an input for the LCA calculations, and the dynamic approach is bi-directional and uses the LCA data within the BIM environment. Genova [61] agrees with the importance of including the EIA data within the BIM environment but shifts the data integration to a parametric design tool that communicates with the design platform, such as Dynamo in Autodesk Revit. This way, the limitations realized by Santos et al. [13] are addressed as a robust database could be linked to the parametric model. Therefore, this intermediate approach is explored throughout this research project considering the addition of variability, uncertainty, and stochasticity within the analysis process.

Additionally, Cavalliere et al. [58] concluded through their detailed paper review that two types of BIM-LCA approaches are used: (1) when the final design of projects is analyzed, thus all necessary data is known to conduct the LCA and (2) at an early design stage, which is based on simplified calculation approaches. This idea supports the importance of Level of Detail (LOD), discussed in various research [58, 13, 14, 32]. Furthermore, Cavalliere et al. [58] emphasize in their research that not all elements undergo the same evolution simultaneously, meaning that typically structural elements are defined with greater detail in the early design process while finishing materials might even be changed after the construction has been started. Additionally, when one considers the early design phase of an infrastructure asset and the evaluation of LCA at that stage, it must be pointed out that there is a mismatch between designers and sustainability personnel/experts [19]. Architects and engineers, who are involved in the early design phase, are knowledgeable about design aspects and know less about how to conduct an LCA study correctly. Therefore, a tool that assists designers with numerical or visual output is crucial, so they can clearly see the effect of their design choices. However, this user-friendly aspect is still missing in most investigated frameworks.

In contrast to the idea that the more detailed the project, the higher the environmental impact score, Hollberg et al. [18] pinpointed the misleading habit of designers, namely that in some countries, it is typical to integrate ‘placeholder materials’ into the early design. Meaning, for instance, designing a thick, homogenous concrete wall in the place of the future external wall to indicate the space needed for that object. This behavior, however, would lead to a larger environmental impact score which does not represent the potential impact of the asset. Therefore, raising awareness and suggesting designers to use approximate detailing and layering during early design stages is inevitable to avoid this potential confusion [18].

The connection of LCA tools to BIM modeling can provide a more innovative design process and the possibility to incorporate different sustainable design choices right at the beginning of the design process. However, it must be noted that there is a clear gap between stochastic LCA and BIM-based LCA studies, as recent researches are focusing on improving either one of these fields (see explanation and examples in section 1). Therefore, an absence of potential data structure between these tools creates an interoperability issue. The absence of considering these two fields simultaneously simplifies the actual problem significantly, as each of these fields is already quite complex in nature.

3 Research methodology

Based on the underlying problem and the aim of the project, a three-step methodology can be conducted, and it is presented in Figure 1. Firstly, the knowledge base of the stochastic BIM-based environmental impact assessment framework builds on the knowledge obtained from an extensive literature review in the fields of sustainability in the construction industry, the uncertainty involved in LCA, stochastic approaches to capture uncertainties, and BIM-based LCA applications (presented in section 2), and on interviews with field experts at the Dutch company of Witteveen+Bos. The interviews targeted the experts' knowledge of (1) the current practices of executing an LCA assessment for infrastructure projects, (2) the current connection and communication processes between the LCA, design, and management departments, (3) the benefits and limitations of a BIM-based LCA tool, and (4) their preference on the usability and performance of the framework. Additionally, (5) experts were asked about their experience with uncertainties in construction projects at an early design stage, (6) their insight on the significance and importance of incorporating uncertainties in the environmental impact assessment, (7) their knowledge of the implementation of uncertainties through stochastic methodologies, and (8) on any upcoming technical issues occurring along the calculation process (e.g., interoperability issues between software packages). The aim of the interviews was to identify obstacles in the framework development process and to gather user insight and requirements that the associated calculation tool should be capable of.

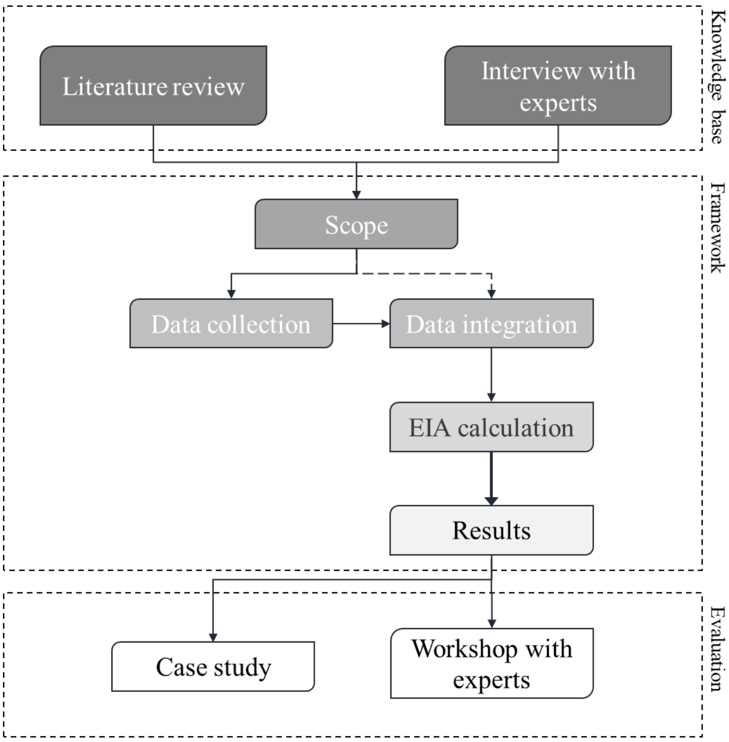

Figure 1 - Research methodology of the stochastic BIM-based EIA framework

The second step of the methodology is to develop the stochastic BIM-based environmental impact assessment framework. This step builds on various BIM-based LCA frameworks and on uncertainties and stochastic approaches involved in LCA assessment concepts. Thus, the framework steps are the following: (1) define the goal and scope of the EIA through user input, (2) generalized BIM-based LCA steps of data collection, data integration, calculation, and results, and (3) generalized stochastic LCA framework steps of LCA model specifications, uncertainty characterization, uncertainty propagation, and uncertainty and sensitivity analysis of the results. Both methodologies build on input-calculation-output thinking (see section 2.3.2) and are developed into a comprehensive stochastic BIM-based EIA framework. The framework development, including a detailed explanation of the listed steps, is described in section 4.

In the end, the framework is evaluated via a case study and a workshop with experts. The case study aims to identify whether the framework can be implemented in the company's practical environmental impact assessment processes. Furthermore, the case study and the development of the stochastic BIM-based environmental impact tool help to identify current limitations and adaptation issues, described in section 5. Next, the workshop aims to present the findings to the company experts and gather their additional insights on the topic, identify potential shortcomings, and validate the usefulness of the developed framework and tool.

4 Framework development

The proposed framework aims to automate the environmental impact assessment within the BIM environment considering the stochastic nature of the design processes of construction projects from the preliminary design to the finalized project. Figure 2 shows the proposed framework that considers six main sections: (1) the LCA model definition, (2) the data collection, (3) the data integration, (4) the uncertainty characterization and propagation, (5) the environmental impact assessment, and (6) the

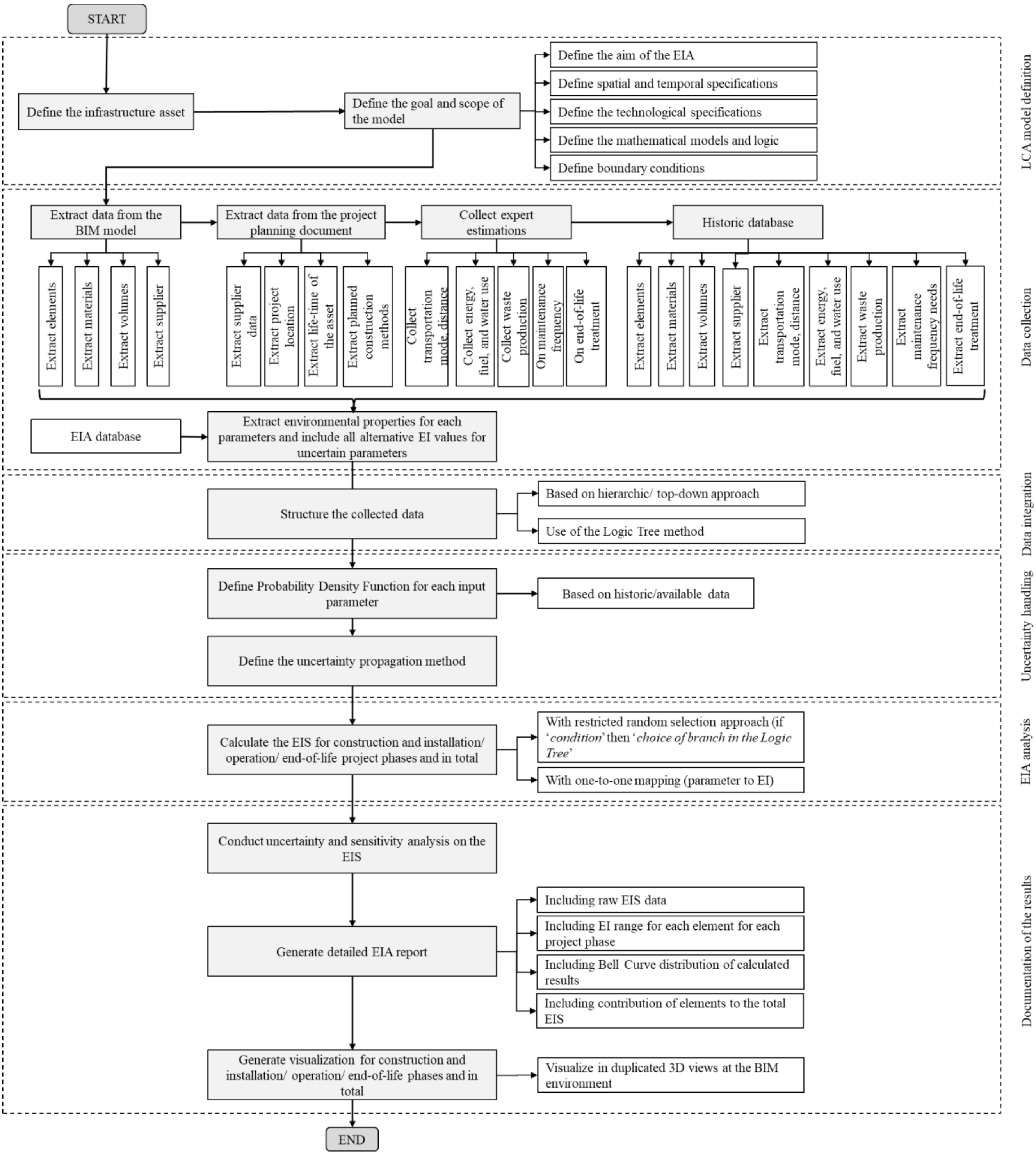

Figure 2 - Proposed framework for stochastic BIM-based environmental impact assessment

documentation of the results. First, determining the basis of the environmental impact assessment through defining the assessment's goal and scope, spatial and temporal specifications, technological specifications, mathematical models and underlying logic, and boundary conditions are defined. Next, the required information for the EIA is collected from the BIM model, the project management document, the collections of expert estimations regarding the specific project, and the historical database. After, the data integration with the uncertainty characterization and propagation is executed. Then, the environmental impact of each element is calculated for the construction and installation, operation, and end-of-life project phases separately and in total for the whole construction project, and the results are analyzed, documented, and visualized. A detailed description of the framework sections is presented below.

4.1 LCA model definition

The first section of the framework aims to define the LCA model used in the assessment process. The stochastic BIM-based EIA is conducted at an 'elemental level', meaning that each construction element's environmental impacts are defined. Therefore, the framework provides a detailed overview by identifying the most influential elements contributing to the overall environmental impact and uncertainty. Additionally, the LCA model definition builds on the steps described in ISO 14040 [4] in the Goal and Scope definition section.

The framework aims to assess the environmental impacts of infrastructure assets at an early design stage through BIM-based LCA methodologies and capture the uncertainties involved in the assessment through stochastic models. Therefore, the dynamic BIM-based LCA approach is implemented in the framework, which allows two-directional data exchange between LCA and BIM. Additionally, including environmental impact data within the BIM environment methodology is adopted as it reduces interoperability issues between software packages and manual errors. Moreover, parametric programming platforms within the BIM environment can easily accommodate uncertainty propagation and stochastic calculation methods.

The framework's scope comprises the environmental impact assessment of constructing a new infrastructure asset and considers a cradle-to-grave investigation, which deals with the production, construction, use, and end-of-life life-cycle stages. These correspond to the A1-A5, B1-B7, and C1-C4 modules in the BS-EN 15978, and they are categorized and summed as (1) construction and installation, (2) operation, and (3) end-of-life environmental impacts at the framework. Each life cycle stage is considered within the framework to achieve a representative environmental impact score and to account for all the shifting environmental burdens between life cycle stages. Next, the system-level cut-off criterion is implemented in the framework that considers the primary production processes and suppliers. This aspect is also reflected in the use of characterization factors of inventory (LCI) and impact assessment (LCIA) phases of the LCA process, thus an aggregated score of the upstream processes is considered, meaning all processes are merged into single values until the material or element is ready to be sold and used.

Furthermore, several environmental impact categories are implemented within the framework, and they are listed in Figure 3. The environmental impact categories are midpoint categories of the applicable resource use, depletion, and waste production. The midpoint impact categories are adapted to provide a generic, worldwide recognized output of the environmental impact analysis. Additionally, an endpoint environmental impact category is implemented in the framework, a single-score indicator that simplifies and merges all the impacts into one monetary value, developed in the Netherlands and known as the Environmental Cost Indicator (ECI) or in Dutch Milieukostenindicator' (MKI). This endpoint category is adopted in the framework as it helps compare design alternatives and construction elements.

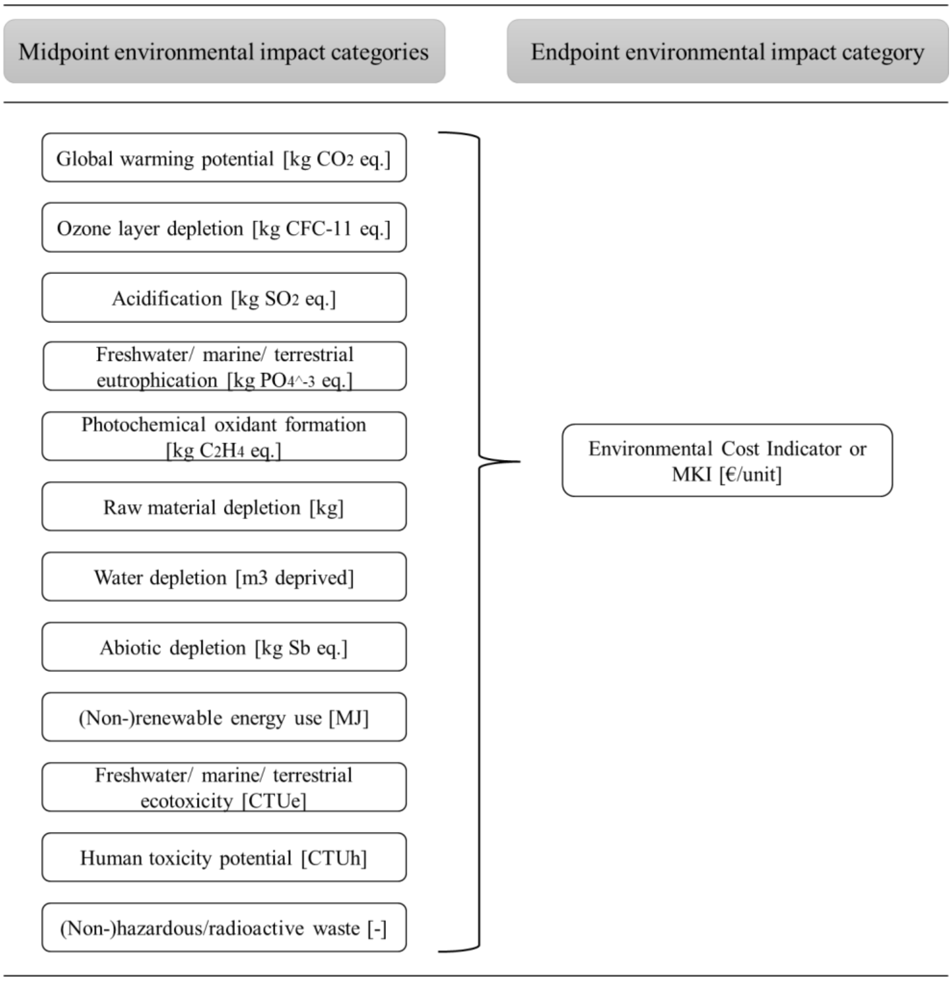

Figure 3 - Incorporated mid- and endpoint impact categories

Lastly, the model definition is expected to be defined by user input. Therefore, this first step of the framework includes some assumption and limitation options to specify the overall project assessment more accurately. These assumptions are related to the location and the infrastructure asset's expected lifetime. Additionally, the framework facilitates the modification of the boundary conditions, cut-off criteria, data requirements, impact categories, and characterization models by incorporating alternative options in a drop-down menu, allowing the investigation of scenario and model uncertainties. The proposed modification options are listed in Table 3, with the default options.

Table 3 - Alternative options for scenario definition and list of default options

Selection categories	Selection options	Default option
System boundary	Cradle-to-gate; Cradle-to-grave; Cradle-to-cradle;	Cradle-to-grave
Cut-off criteria	System-level criterion; Mass-based criterion; Energy-based criterion; Impact-based criterion*;	System-level: only direct production and suppliers
Data requirements	Spatial scope: country-specific/ European/ or global data; Temporal scope: data from the last 5, 10, 20 years, or older; Data sources: primary, secondary, calculations, estimations;	Spatial scope: Global data Temporal scope: within the last 5 years Data sources: primary or estimations
Impact categories and characterization models	ReCiPe; TRACI; CML2002;	ReCiPe
Assumptions and limitations	Project location: the Netherlands, Europe, Worldwide; Expected lifetime: between 0-20, 20-50, 50-80, or 80+ years ranges;	Project location: the Netherlands Expected lifetime: 50-80 years

*Impact-based cut-off criteria apply for each environmental impact that contributes to the overall environmental impact with less than 2%.

4.2 Data collection

This framework phase aims to collect the required information to perform the stochastic BIM-based environmental impact assessment. There are five sources which the data is collected from, and these are (1) the BIM model, (2) the project management document, (3) the expert estimation data sheet, (4) the historical database, and the (5) the environmental impact assessment database.

The BIM model is the basis and starting point for collecting the required data for the environmental impact assessment. Therefore, information about the construction project is first collected from this source. This involves the construction elements, material types, quantities, qualities, and supplier data. Generally, a preliminary BIM design lacks detailed information regarding the project and all life cycle information necessary for the environmental impact assessment; therefore, it must be complemented with information available in the project management document.

From the project management document, information about the construction project's location, further supplier data, the planned lifetime of the construction asset, and an outline of construction methods can be extracted. Additionally, the collection of expert estimates provides information about the assumed transportation modes and distances between manufacturers and the construction site, approximate energy, water, fuel consumptions, and waste production along the construction processes, the estimated maintenance needs and their frequencies, and the potential end-of-life treatment of the construction asset. These pieces of information can already be part of the project management data or collected in a separate datasheet. Either way, this information is explicitly collected regarding the infrastructure project at hand.

A historical database is included in the data collection process as finalized decisions, and thus accurate data are limited in an early design phase when the environmental impact of the construction project is investigated. Therefore, a historical database is utilized to collect data about similar infrastructure projects. The historical database provides information on the construction elements, materials, quantities, and qualities, on suppliers, on the actual lifetime of the infrastructure asset, construction methods used, transportation methods and distances, energy, water, fuel used, and waste byproducts produced, information on maintenance frequencies and needs, and end-of-life treatment processes. Therefore, whenever information regarding any input parameter of the infrastructure project is missing, the historical database provides several alternative solutions that can be used.

Lastly, when all the required information is collected from the sources mentioned earlier, the corresponding environmental impact data must be gathered for the environmental impact assessment. The environmental impact data used are an aggregate score for the inventory (LCI) and impact assessment (LCIA) processes at the life cycle assessment. The corresponding data is collected from the environmental impact database in accordance with the uncertain information available at an early design stage and the alternative choices for each required input parameter. Moreover, the environmental impact database is linked directly to the framework allowing easy access to the environmental impact information.

Regarding the early stage of the infrastructure project, information in the BIM model and project management document is either (1) known and sufficient for EIA, (2) segments of information are known but insufficient for EIA, or (3) unknown. Known and sufficient information means that all input parameters for the environmental impact assessment of a construction element are known. Insufficient information about the construction element means some of the input parameters are known, but not all of them. For example, a construction element of a beam is defined as a prefabricated concrete element with its quantity; however, its quality regarding its strength or reinforcement content is unknown. Lastly, unknown input parameters regarding a construction element mean that most input information is vague or undefined.

When information is missing or insufficient, a random value is selected from a predefined list of alternatives that is capable of fulfilling the input parameter's functionality. This list of alternatives is built on characterizing the input parameter into a broader group or determined based on expert judgment. For instance, the transportation mode can be unknown during the early design stage; therefore, they could be categorized into transportation via cargo trucks, vessels, trains, Etc. Then, within each group, a number of alternatives are collected as potential solutions. The information-gathering process for uncertain input parameters is visualized in Figure 4.

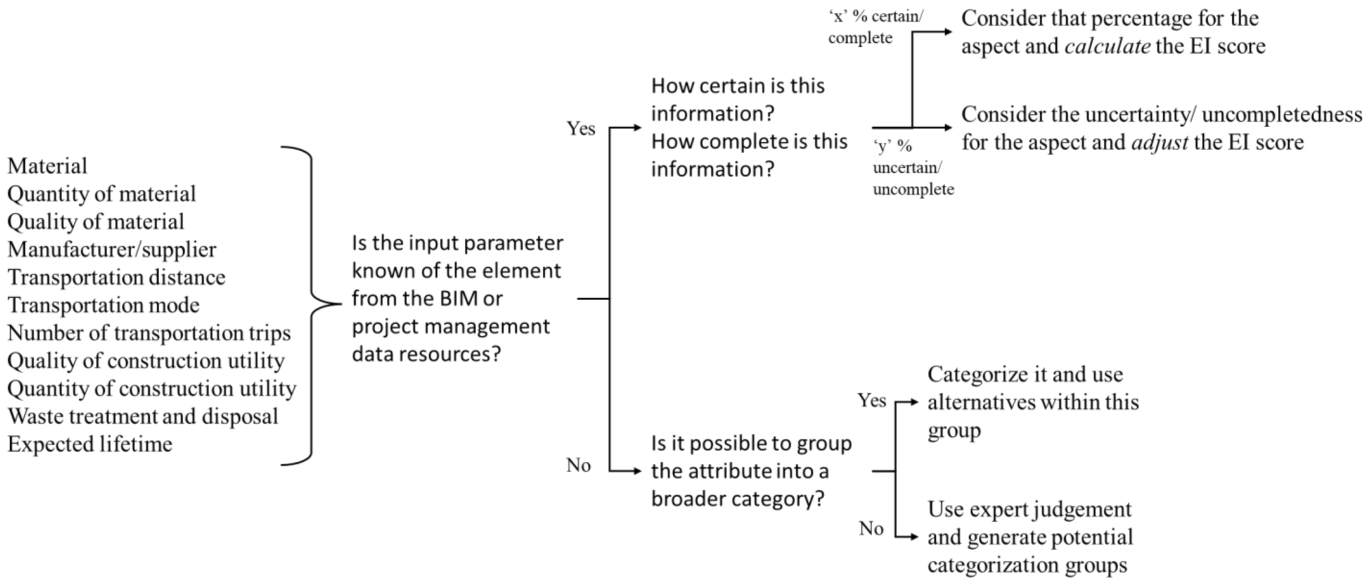

Figure 4 - Information gathering process for uncertain input parameters (input parameters are listed in the left column)

Note that certainty and completeness of the information regarding input parameters are determined based on a comparison between available information in the BIM model and project planning document, and the historical database. Additionally, the likelihood of an input parameter occurrence is also investigated with information available within the historical database. Then the comparisons are translated to percentages and are used in the environmental calculations.

4.3 Data integration

The collected data must be integrated to assess the construction asset further from an environmental impact perspective. As the framework is developed for an elemental level of evaluation, the data must also be structured at an elemental level, meaning that the environmental impacts are going to be determined for each element separately for the manufacturing and construction, operations, and end-of-life stages. In this way, the elements and their environmental impacts can be compared, and the designer can easily pinpoint potential improvements within the project.

Moreover, the Globally Unique Identifier (GUID) embedded in the BIM environment is used to trace the components within the framework. As the name suggests, the GUID is a specific ID or name that ensures that the data remains structured, unique, and traceable [62]. This aspect is crucial within the framework, and it allows later to import the EIS data back to the BIM model after the EIA calculation has been carried out.

The data integration process is executed within the BIM environment. The input parameter sources are external databases and documents in the framework, and they are used as plugin options. This loose linkage between the framework and the data resources allows flexibility and the alternation possibilities of input information. Additionally, this linkage enhances the development of different scenario-based evaluations described in section 4.1.

The integration of the collected data, shown in Figure 5, is executed through a hierarchic methodology, also called a top-down approach. This approach investigates the infrastructure asset at hand and breaks down the project into construction elements, materials, quantities, suppliers, associated transportation, utility use, waste production, maintenance, and end-of-life treatment. The hierarchy is applicable in the same order as the input parameters listed. Then the hierarchical approach is complemented by the Logic Tree concept, meaning that at each step down in the hierarchic structure,

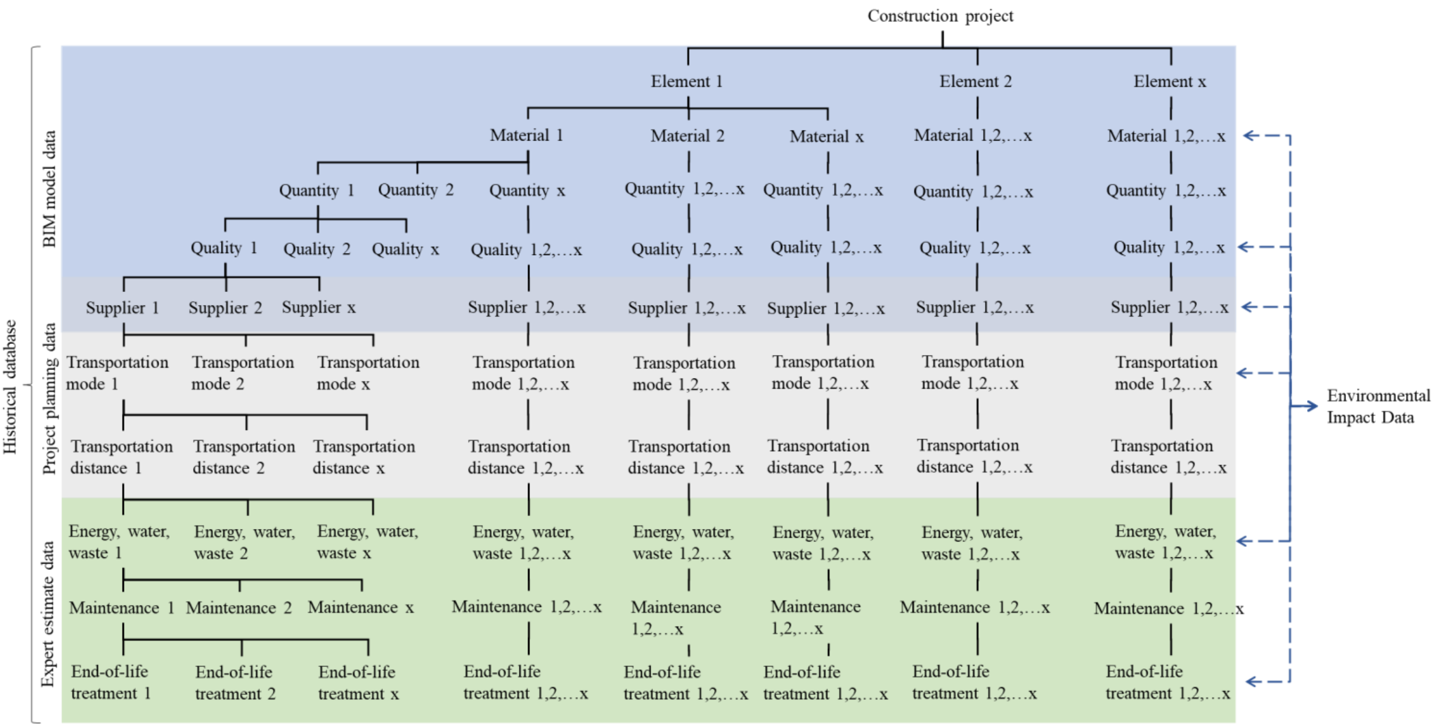

Figure 5 – Logic Tree of the data integration process (Adapted from Eldik et al. [71])

there are various alternative input parameters that the framework can obtain. The Logic Tree concept combined with the hierarchic approach is implemented as it provides a clear navigation path by allocating information to each construction element at each hierarchical step. Consequently, it enhances the restricted random variable choices in the Monte Carlo Simulation. The tree structure helps to randomly select a parameter for an element at a specific level in the hierarchy, move down one step, and select the next parameter randomly but from a corresponding set of variables. For instance, the pile foundation elements can be made out of concrete, steel, timber, or composite; however, each material alternative would result in a different set of transportation possibilities, utility needs, maintenance requirements, and end-of-life treatment.

Additionally, the input parameter options are not limited to single solutions or values due to significant uncertainty at an early design stage. However, they are defined as sets of variables or within minimum and maximum ranges. The sets of variables are present for the input parameters collected from the BIM model, the project management document, and the historical database. At the same time, the minimum-maximum ranges are applicable for the expert estimate data sheet.

Lastly, input parameters and the associated environmental impact data are integrated with conditional statements. The conditional statement is asked at each step along the hierarchic Logic Tree structure. The statement itself, in simplified terms, is: if ‘condition’ is true, then select EIA data; else, do not select anything. For instance, if the element is made of concrete is true, then select EIA data for concrete; otherwise, do not select anything. With this approach and with ‘for loops’, each condition can be investigated in the Logic Tree; thus, all alternative solutions are investigated for uncertain aspects.

4.4 Dealing with uncertainties

4.4.1 Uncertainty characterization

Naturally, uncertainties are present throughout the design stages of infrastructure projects. Therefore, all parameter-related uncertainties must be defined to be able to use them in the environmental impact assessment. At an early design stage, there are uncertainties involved in most input parameters. Therefore, these uncertainties must be collected and characterized to proceed with the environmental impact assessment.

In general, the framework considers three categories of uncertainties: scenario, model, and parameter uncertainties, described in section 2.3.1. Scenario and model uncertainties are captured through the previously mentioned drop-down menu in model definition 4.1, and parameter uncertainties are captured through the variations of data collection 4.2. Parameter uncertainties are assessed at a more detailed level, with sets of input parameter options, quantities, and environmental impacts. Uncertainties related to data variation between environmental impact databases are captured using a pedigree matrix. The pedigree matrix defines reliability, completeness, and temporal, spatial, and technological correlations. The qualitative description of the pedigree matrix is presented in section 2.3.1.

Uncertainty characterization aims to define the Probability Distribution Function of each uncertain project information and characterize them based on available data. In other words, the uncertain input parameters must be defined based on statistical functions that describe the likelihood of the outcome that a random variable can take from a range of possible values. In general, probability functions are built on available data, comprising the information collected from commercial databases, company databases, and research findings in a geographical context. Unfortunately, the mentioned databases in the construction industry are not always available to the public or are limited in their extensiveness. Therefore, the historical database mentioned earlier is used within the framework to collect the 'available data' and use it to determine the probable input parameters of the different construction components. Therefore, the historical database is expected to be updated frequently by company experts, and outdated information must be excluded to increase the precision of the framework.

Consequently, the discrete probability distribution function is adapted within the framework with Poisson distribution to model how many times an event is likely to occur within a specific timeframe. This means that each uncertain input parameter can obtain a specific value from the historical database with a certain likelihood. When limited information is available in the historical database, the expert estimation data sheet is used as a second source. However, note that the expert estimates data sheet builds on continuous distribution with uniform distribution and minimum and maximum boundary values.

4.4.2 Uncertainty propagation method

The stochastic methodology of Monte Carlo simulation is implemented in the framework to propagate uncertainties. The Monte Carlo simulation method is a mathematical model to predict the outcome of an uncertain event. It builds on historical data, meaning that it considers the potential outcome of the sample and the likelihood that an outcome occurs. Defining the likelihood of the specific values depends on the historical data; therefore, the Monte Carlo method and the probability distribution function explained in section 4.4.1 are utilized together.

4.5 Environmental impact assessment

Once all information is gathered and integrated, the life cycle impact assessment calculation can be executed. The simplified environmental impact calculation can be used as the framework uses characterization factors extracted from the environmental impact database. Here the environmental impact scores are equal to the quantities of input parameters multiplied by the characterization factors. Additionally, as mentioned in section 4.1, the environmental impact scores are calculated at an elemental level for manufacturing and construction environmental impact (EI_x^{MC}), the operational environmental impact (EI_x^{O}), the end-of-life environmental impact (EI_x^{EOL}), and in total (EI_x). The calculation methodology to determine the environmental impact scores per element per project phase is adapted from Santos et al. [13] and presented in Equations 1-4.

$$EI_x = EI_x^{MC} + EI_x^{O} + EI_x^{EOL} \tag{1}$$

$$EI_x^{MC} = L * \underbrace{\sum_{a=1}^{i} (Q_a^M \times EI_a^M)}_{\mathbf{A1-A3}} + \underbrace{\sum_{b=1}^{j} (D_b^V \times Nt\_1 \times EI_b^V)}_{\mathbf{A4}} + \underbrace{\sum_{c=1}^{k} (Q_c^{Con} \times EI_c^{Con})}_{\mathbf{A5}} \tag{2}$$

$$EI_x^{o} = \underbrace{\sum_{a=1}^{l} (Q_a^M \times N_r \times EI_a^M)}_{\text{B2-B4}} + \underbrace{\sum_{b=1}^{o} (Q_b \times EI_b) \times n}_{\text{B6-B7}} \tag{3}$$

$$EI_x^{EOL} = \underbrace{\sum_{c=1}^{k} (Q_c^{D.con} \times EI_c^{D.con})}_{\mathbf{C1}} + \underbrace{\sum_{a=1}^{p} (D_a^V \times N_t \times EI_a^V)}_{\mathbf{C2}} + \underbrace{\sum_{b=1}^{q} ([Q_b^M \times Q] \times EI_b^{WT})}_{\mathbf{C3}} + \underbrace{\sum_{c=1}^{r} ([Q_b^M \times (1-Q)] \times EI_c^D)}_{\mathbf{C4}} \tag{4}$$

Where L is the total amount of elements used along the construction process, including wasted materials or components during the installation phase in percentage; Q_a^M is the quantity of materials per element; EI_a^M is the corresponding environmental impact of the material; D_i^V is the distance between the supplier and the construction site; Nt_i is the number of transportation trips; EI_i^V is the corresponding environmental impact of the transportation mode; Q_c^{Con} is the utility consumption through the construction process; EI_c^{Con} is the corresponding environmental impact of the utility used; ‘i’ is the number of materials per element ‘a’, ‘b’ is the transportation mode with the variation of ‘j’; ‘c’ is the applicable utilities with the variation of resources ‘k’; N_r is the number of intervention times for an element or material; Q_b is the consumption of utilities used per year; EI_b is the environmental impact of the consumption of utilities; n is the operation time of the construction asset in years, ‘l’ is the number of construction materials and components to be replaced; ‘o’ is the utility types used during the operation of the construction asset; $Q_c^{D.con}$ is the utility consumption through the demolition and deconstruction process; $EI_c^{D.con}$ is the corresponding environmental impact for the utilities; Q_b^M is the amount of material that is treated; Q is the percentage of materials that are treated; EI_b^{WT} is the environmental impact of the waste treatment process; EI_c^D is the environmental impact of the disposed materials; ‘k’ is the utility types; ‘p’ is the transportation mode; ‘q’ is the treated materials; ‘r’ is the disposed material.

Furthermore, when the calculations are executed, a random value is selected for each variable in the equations, Equation 1-4. This random selection process is explained in detail in section 4.3. The environmental impact calculation is executed 10.000 times to capture variability in the results through different input parameters. The 10.000 runs are sufficient to explore all potential combinations of uncertain input parameters, and this specific value has been established by various researchers [46, 63, 64].

It must be pointed out that each of the variables in the equations described above is potentially uncertain values, and the different variables are correlated with each other. For instance, an uncertain material choice would affect the quantity and quality of the material itself but also influences the potential supplier, transportation needs, energy and water use, waste by-products, Etc. Additionally, it naturally affects the related environmental impacts, and the selected elements can influence the properties of the contact elements too. Nevertheless, the interrelatedness of input parameters and the correlation between construction elements are simplified to the hierarchical chain visualized in Figure 5, following the information detailing steps of the construction elements (from top-down).

4.6 Uncertainty and sensitivity analysis

Uncertainty analysis captures all underlying uncertainties involved in the environmental impact assessment. Uncertainties in this report are embedded in the steps previously described of the stochastic BIM-based environmental impact assessment concept (specifically in sections 4.1, 4.2, 4.4.1, and 4.4.2). Uncertainty analysis focuses on the input information variability and the concepts used, categorized in this research with model, scenario, and parameter uncertainties (described in more detail in section 2.3.1). Additionally, two uncertainty methods are used in this research: input uncertainty quantification and probabilistic assessment. The first method is associated with the uncertainties related to each input parameter collected through logical associations and characterized as either known and sufficient, insufficient, or unknown information described in section 4.2. For the input parameters that are insufficient or unknown, historical databases and expert estimations are gathered to support the probabilistic uncertainty assessment method. Meaning when uncertainties are categorized as either insufficient or unknown, then a set of probable inputs are collected and used. Moreover, the probable input parameters, including their usage frequency, are collected, meaning that these uncertainties are categorized with Posions distribution, described in section 4.4.1. Lastly, the Monte Carlo method is used as the probabilistic assessment method, described in section 4.4.2, that builds on the previously mentioned sets of variables described in section 4.2.

The sensitivity analysis relates to the variations resulting in the outcome. Therefore, the sensitivity analysis builds on the generated 10.000 alternatives. The framework incorporates the factor screening sensitivity analysis approach, which identifies the parameters that most significantly influence the overall environmental impact score. The sensitivity analysis process is partially executed by manually changing the scenario- and model-related information in the drop-down menu described in section 4.1. Then, the sensitivity analysis itself is carried out through the analysis of the results, where the raw data are organized to capture the (1) ranges of possible outcomes per element per impact category, (2) different plots are generated to visualize the environmental impact score distributions, and (3) pie charts are generated to show the most influential construction elements, further description on the results are in section 4.7.

4.7 Visualization and documentation of the results

In accordance with the project's scope, to provide meaningful feedback to the experts involved in the early design stage of the project, two documentation types of the results will be generated. The first is visual feedback in the BIM environment through color-coding in duplicated 3D views, and the second is a detailed report containing visuals, graphs, and calculated EI scores.

The visualization of the environmental impacts is executed through heat mapping, where the warmer regime represents the higher impacts, and the colder regime displays the lower ones. The color coding is based on the mean ECI/MKI score per element, considering both the aggregated total values and the main stages of manufacturing and construction, operation, and end-of-life. The contribution of each element to the total environmental impact at the different phases is defined through percentages as $EI_p^r = \frac{EI_x}{EI_{total}} * 100$ [%]. Where EI_p^r is the relative environmental impact of an element at a specific phase; EI_x is the environmental impact of a specific element at a project phase; and EI_{total} is the sum of the environmental impacts of all elements at the specific project stage.

Then color-coded groups are formulated in each 10% to capture the variability of the impacts. The percentage groups and the associated colors are listed in Table 4. However, note that the higher regime of environmental impacts with more than 30% is rare; therefore, this group has a bigger interval. Additionally, according to ISO 14040 [4], the environmental impacts contributing less than 2% to the total score could be potentially disregarded. Therefore, the least influential components are also identified through this color coding.

Table 4 - Intervals specified for the color-coding scheme

Contribution to EIS per element	Color-code	
30% ≤ $\boldsymbol{EI_x}$	Red	■
20% ≤ $\boldsymbol{EI_x}$ < 30%	Orange	■
10% ≤ $\boldsymbol{EI_x}$ < 20%	Yellow	■
2% ≤ $\boldsymbol{EI_x}$ <10%	Yellow-green	■
$\boldsymbol{EI_x}$ <2%	Green	■

Additionally, the stochastic nature of the calculated ECI/MKI values is captured through transparency. Due to all the variations and uncertainties incorporated in the calculations, the results have a distribution range that must also be visualized. Therefore, the standard deviation is calculated from the ECI/MKI scores to capture how dispersed the resulting scores are in relation to the mean value for each element. The standard deviation is then recalculated in terms of percentages. The calculated percentages then show how certain the outcome is and, consequently, how certain the contribution to the overall project score is. The smaller the standard deviation value recalculated in percentages, the more certain the outcome is. Visualizing this aspect through transparency is done by the smaller the calculated percentage, the less the construction element is made transparent, and the greater the percentage, the element is visualized more transparent. The greatest transparency category is limited to 50 as the visibility of the element and color would be unrecognizable beyond 50% transparency. The transparency ranges are listed in Table 5.

Table 5 - Intervals specified for the transparency scheme

Standard deviation (SD)	**Transparency**
$90\% \leq \boldsymbol{SD}$	50
$80\% \leq \boldsymbol{SD} < 90\%$	45
$70\% \leq \boldsymbol{SD} < 80\%$	40
$60\% \leq \boldsymbol{SD} < 70\%$	35
$50\% \leq \boldsymbol{SD} < 60\%$	30
$40\% \leq \boldsymbol{SD} < 50\%$	25
$30\% \leq \boldsymbol{SD} < 40\%$	20
$20\% \leq \boldsymbol{SD} < 30\%$	15
$10\% \leq \boldsymbol{SD} <20\%$	10
$2\% \leq \boldsymbol{SD} <10\%$	5
$\boldsymbol{SD} < 10\%$	0

Visualizing the mean ECI/MKI score and the associated uncertainties per construction elements in the BIM environment aims to assist designers. The visualization provides immediate feedback on the color-coding and transparency aspects in 3D views. With the visual representation of the environmental impacts, designers can identify construction elements and processes contributing to the greatest extent to the project's overall environmental impact and highlight improvement possibilities.

Next to the visualization, the assessment outcome provides a detailed report that contains a 3D overview with color-coding, tables with all calculated environmental scores, and an overview table with minimum, maximum, and mean values for each construction phase and in total. Additionally, the report shows bell curve distribution graphs, box whiskers plots, and pie charts showing each element's contribution in percentages. The documentation report aims to provide quick access to all information regarding the stochastic environmental impact assessment results to any users. In this way, the project managers, collaborating with the designers, can contribute to achieving a more sustainable infrastructure project.

5 Implementation and case study

In order to analyze and evaluate the proposed framework, a tool was developed which incorporates the environmental impact data with the preliminary design for infrastructure assets. The architecture of this tool is visualized in Figure 6. The basis of the tool is a BIM environment, namely Autodesk Revit, that allows both to analyze the current model and display the results in the required view. For analysis purposes, the Revit plugin Dynamo is used, which is a Python-based visual programming interface that allows users to customize information flows in the Revit model [65]. In line with the variety of tasks that can be programmed within Dynamo, the data collection, uncertainty propagation, data integration, environmental impact calculations, stochastic variation generation, and reporting and visualizing the output are coded within this interface. The input data is collected from the Revit model itself, the available project management data, the ECI/MKI is taken from the Dutch National Environmental Database (NMD), and the midpoint impacts are collected from the Eco-invent database. The latter two datasets needed to be exported to Excel, which could then be imported into the Dynamo interface. Moreover, these two databases are merged in Excel. Then the outcome is reported in Excel and visualized in the Revit model.

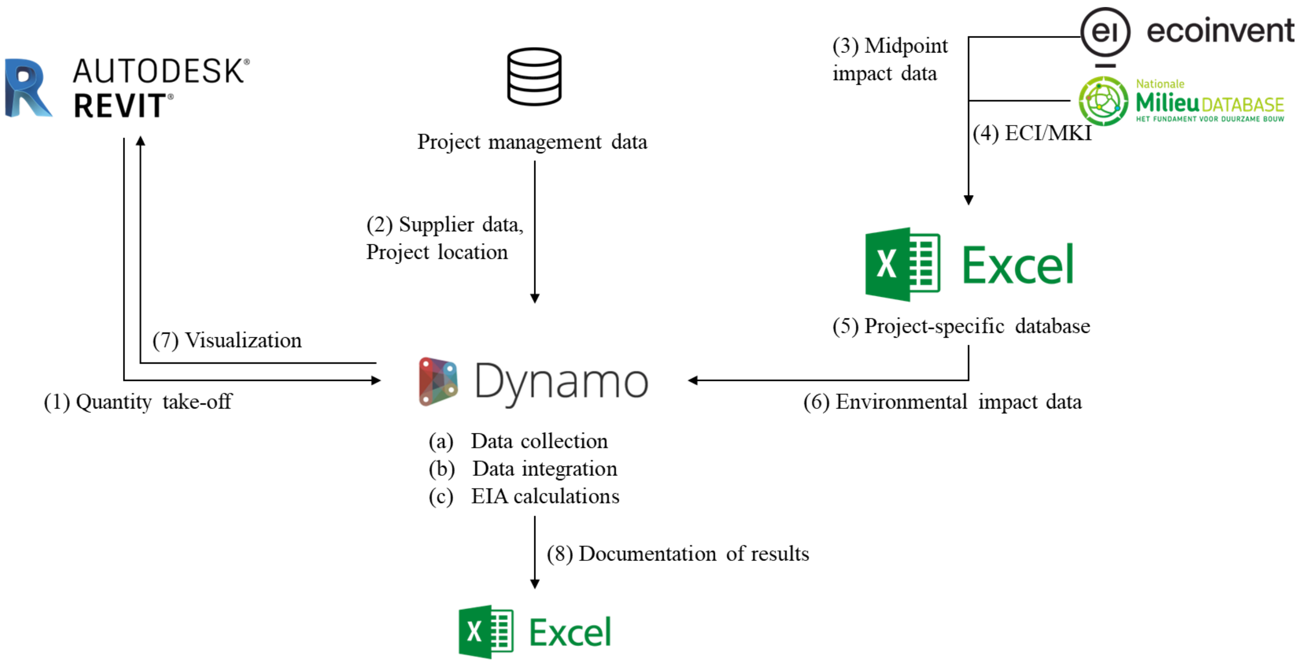

Figure 6 - Architecture of the developed tool

5.1 Case study - bridge asset

The developed tool is tested with a case study of a bridge asset located in the Netherlands. The bridge aims to provide shorter access between industrial properties with motorized vehicles, cycling, and walking in two directions. The bridge asset comprises of 11 types of main components, namely the foundation piles, supporting beams, sheet piles, transition plates, bridge deck, abutments, cycling path, road pavement, strip, sidewalk, and the middle berm that separates the motorized and cycling traffic, sand-cement type soil stabilization, and PVR covers (see in Figure 7). In total, the preliminary design contains 147 elements, most of which are made from in-situ – reinforced – prefabricated concrete, steel, or asphalt.

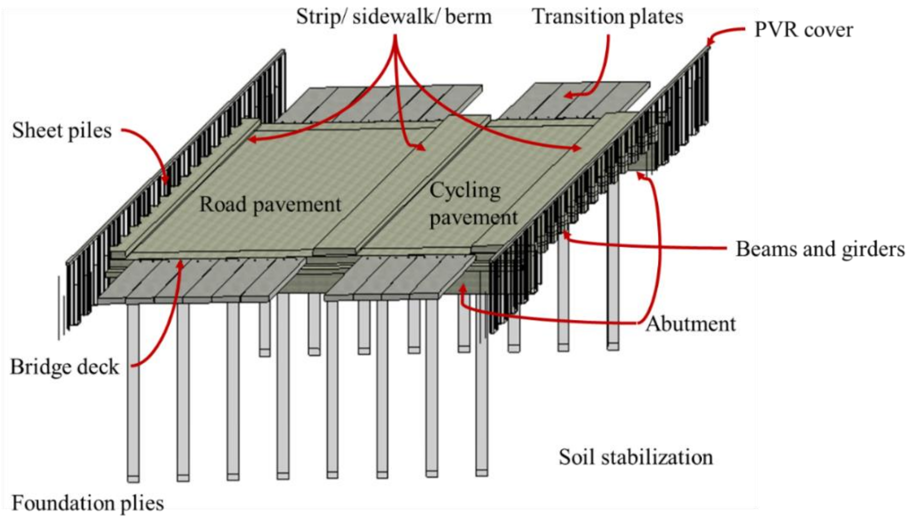

Figure 7 - Visualization of the bridge asset at an early design stage showing the identified groups of main construction elements

The outline of the case study is vastly changing from the preliminary design through the final design until the construction design. This aspect is natural for any project; however, the significant difference between the final and construction design is not expected. This shows that there are still many uncertainties involved in the project at the final design stage. The project's progression (as a Revit model) can be seen in Figure 8, and the volume changes are listed in Table 6. The most significant changes occur in the volumes for the pile foundation, abutment, sidewalk, and soil stabilization, and variation occurs either in material choice or quality or both for almost every component (except the sheet pile 'railing' that is definite and does not change throughout the project). Note that the specific material and supplier choice is decided in most cases along the construction process, considering the actual market aspects such as price and availability of the material or component.

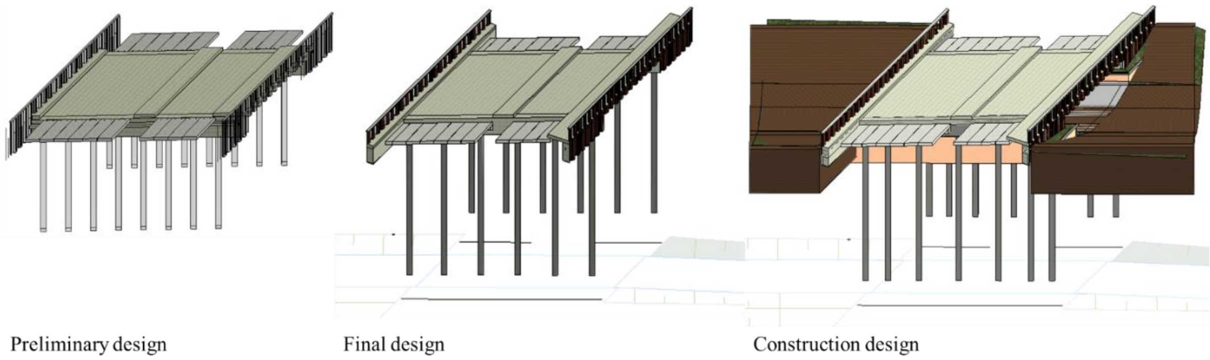

Figure 8 - Development of the bridge asset

Table 6 - Volume changes through the design process of the bridge asset

	Volumes [m3]			**Change in volume**
	Preliminary design	Final design	Construction design	(From preliminary to construction design)
Foundation piles	32,497	35,648	41,589	128 %
Beams	26,577	28,011	27,986	105 %
Sheet piles	1,455	1,740	1,771	121 %
Transition plates	17,780	18,702	18,702	105 %
Bridge deck	45,498	47,561	46,955	103 %
Abutment	44,377	63,279	185,752	419 %
Road and cycling pavements	1,716	1,600	1,600	93 %
Strip/sidewalk/middle berm	14,634	23,951	23,820	163 %
Soil stabilization	56,288	55,642	282,717	502 %
PVR cover	0,559	0,986	1,191	213 %

Figure 8 and Table 6 show the importance of incorporating uncertainties in the environmental impact assessment at an early design stage of an infrastructure project. Identifying changes in percentages helps to point out completeness and certainty issues related to construction elements. Thus, modifications of the materials and volumes are adjusted in the assessment process based on associated percentage differences between the preliminary design and the historical database that collects similar project data. These two aspects are just an example of immediately conspicuous uncertainty and issues related to completeness; section 5.2 describes further specifications implemented in the developed tool and case study.

5.2 Implementation and tool specifications implemented in the case study

Some limitations and simplifications are executed in the tool development due to the project's time frame and limited programming knowledge at the beginning of the implementation process. The specifications and simplifications are described in the same structure as the framework development, so a more straightforward correlation between the two can be obtained.

5.2.1 Data model definition

The developed tool is limited to incorporating all default options listed in Table 3. The drop-down menu with all the other possibilities has not been developed due to time and knowledge constraints. However, the data model definition, or the basis of the assessment, deals with all scenario-related and model uncertainties. Both uncertainties are implemented with safety factors to still generate and investigate the different scenarios and models in the results of the tool's output. A safety factor of a random multiplier between ± 25% is selected to account for scenario uncertainty. This range of potential multipliers is defined based on the research findings of Zang et al. [64] and the safety factor suggested by Hollberg et al. [19] (sections 2.3.1 and 2.3.2). Additionally, a random number between ± 5% is implemented to account for model uncertainties. The safety factor for model uncertainty is selected in line with the research of Mojtaba and Imad [66]. Note that a subtraction or surcharge of 30% in extreme cases is significant; therefore, developing the drop-down menu options in the future expansion of the tool is highly recommended.

5.2.2 Data collection

The data collection for the environmental impact assessment is complicated as most input parameters are either insufficient or unknown. Additionally, there is a great need for expert estimations and historical databases. Nevertheless, the required information is collected as described in the framework; first, extract all the information from the BIM model, then complement this with information available in the project management data. Lastly, collect and adjust input parameters based on the expert estimation sheet and historical database.

First, the elements are extracted from the BIM model and grouped based on their functionality. The materials and volumes of the elements are mostly available in the model; thus, they are extracted. This information's completeness and certainty are insecure, as demonstrated in Table 6 and Figure 8. Therefore, materials and their volumes are preliminary extracted from the BIM model and adjusted according to information on historical data on commonly used materials and quantities. Moreover, the quality description and manufacturer data are missing from the BIM model. Therefore, several material qualities and suppliers are investigated as alternatives, 2 to 15 for each element, for concrete, reinforced concrete, prefabricated concrete elements, steel, timber, composite, asphalt, sand-cement mix, and Poly Vinyl Rubber (PVR).

The project management data provided information only on two additional suppliers and manufacturers. Therefore, the lack of information at an early design regarding manufacturers leads to uncertain information on material qualities, upstream processes, transportation modes, and distances between the construction site and suppliers. Additionally, the project management data provided information on the infrastructure project’s location; therefore, some estimations regarding potential transportation modes and distances could be made via expert intel. For instance, transportation mode is assumed to be either via cargo trucks, freight trains, or vessels, and the distances are estimated between the range of a minimum of 5 km to a maximum of 300 km. As the project management already incorporated various assumptions, this document is supplemented with expert estimation information. The estimations are collected via an additional interview with the project leader. The expert estimation ranges are collected in Table 7 below. Note that each estimation aimed to collect wide ranges to capture the extreme alternatives. A discussion is made on this matter in section 6.

Table 7 - Expert estimations determined via an interview with the project leader of the project

Estimated input variables	Minimum value	Maximum value	Unit
Transportation distance	5	300	km
Utility for (de)construction*	200	3000	liter
Utility operation**	4000	7500	kWh
Excess material use	1	1,5	-
Number of transportation between sites	1	20	-
Number of interventions	0	Int. [year] / n [year]***	-
Recycling rates	0	1	-

* Operation of machinery during construction of the infrastructure asset
** Energy use during the operation of the infrastructure asset
*** Each construction element has different intervention needs in years (int.), therefore the upper limit is calculated by int./n, where n is the lifetime of the infrastructure asset

Next, the historical database is created based on a questionnaire held between experts. The questionnaire aimed to collect information regarding all relevant input parameters for a bridge construction with similar dimensions. The historical database defines the certainty and completeness of an input parameter choice with their quantities. For instance, reinforced concrete beams are used at bridge constructions 4 out of 10 times, and the volume of the element ranges between 15 to 45 m^3. Note that the historical database is not limited to material choice and quantities but includes all input parameters needed for the environmental impact assessment.

Lastly, the environmental impact data is collected from the Eco invent and the Dutch National Environmental Impact databases. These two environmental impact databases are commercially available products; therefore, access to all data and the direct connection between the BIM environment and the databases are legally not viable. Therefore, a project-specific environmental impact database is created by extracting alternative options for each input parameter. An exhaustive overview of the extent of the project-specific database is shown in Table 8.

Table 8 - Number of alternatives for each attribute

Element attributes	**Groups**	**Nr. of alternatives**	**Description**
Material	Concrete	8	With different concrete strengths between C20 and C50, with more alternatives in C30-C45.
	Reinforced concrete	8	With different concrete strengths between C20 and C50, with more alternatives in C30-C45. Furthermore, with various reinforcement content from 5-20% and three different types/sizes of reinforcing steel.
	Prefab concrete	15	With a variation in the strength of the concrete, the reinforcement content, and the manufacturing process
	Steel	5	With a variation in strength and manufacturing process
	Asphalt	14	With a variation on asphalt, zoab-asphalt, asphalt with concrete crush, 0-50% recycling rates

	Sand-cement mix	3	With a variation in cement content
	PVR	2	Poly Vinyl Rubber is very specific, and hard to find alternatives
	Timber	2	With a variation in origin
	Composite	2	With a variation in material content
Transportation mode	Cargo truck/lorry	11	With a variation in carrying capacity, fuel consumption, and fuel type (diesel/gas)
	Freight train	1	An average value for electric trains in Europe
	Vessel	2	With a variation in carrying capacity, but each one is for inland waterways
Utility mix (quality)	Diesel	4	With a variation in construction machines and different fuel consumption
	Gas	4	With a variation in construction machines and different fuel consumption
Waste treatment	-	3	Average recycling rates of concrete, steel, and asphalt
Waste disposal	-	2	An average value for Europe and the Netherlands

Additionally, the environmental impact characterization factors are extended with the pedigree matrix concept. However, as there were (1) no possibility to use various different environmental impact data sources, (2) no specific information on the quantification process of the pedigree matrix is found, and (3) the quantified values that are found vary from research to research, a simplified approach is used. This simplified method mimics the data variation between different environmental impact databases. The simplified approach modifies the collected environmental impact data with ± 1-5%.

Lastly, note that all data sources, except the data extracted from the BIM model, are plugin Excel tables in the tool.

5.2.3 Data integration

The integration of all input parameters is carried out via a Python code block in Dynamo. This node option is selected as it uses phyton programming language desirable for the conditional random selection process, described in section 4.3. Each input parameter condition is investigated in the programming window through '*if*' statements and '*for*' loops. The conditions are investigated in accordance with the hierarchic tree structure described in section 4.3. When a parameter is selected from the options, that branch is selected on the tree structure. Then the following conditional statement is investigated until all input parameters are selected for the run.

The data integration is technically conducted through the conditional random selection process for each input variable described in section 4.3 and integrated with the environmental impact assessment equations presented in 4.5.

5.2.4 Dealing with uncertainties

5.2.4.1 Uncertainty characterization and propagation method

The input parameter sets are collected with a wide range of variety during the data collection process and propagated with percentage multipliers. The plug-in data are organized in separate Excel sheets to provide a structured way of accessing each data group in the hierarchic steps.

Therefore, the collected input parameters and the collected sets of variables can be easily used at the discrete probability distribution function. The Poisson distribution function is used through the Monte Carlo method as described in the framework development sections 4.4.1 and 4.4.2.

5.2.5 Environmental impact assessment

The proposed calculation method is implemented in the Phyton node in Dynamo. No simplifications are made compared to the developed framework.

5.2.6 Uncertainty and sensitivity analysis

As explained in the framework in section 4.6, the uncertainty analysis is carried out throughout the previous steps in the developed framework and, thus, tool. Note that the scenario and model uncertainties are obtained in the tool via safety factors, as the drop-down menu turned out to be complicated to program. Therefore, these uncertainties are automatically included within the 10.000 runs. No changes occur regarding the sensitivity analyses.

5.3 Visualization and documentation of the results

The visualization and documentation of the results are carried out in line with the described methodology explained in the framework development section 4.7.

In principle, the tool automatically generates and calculates 10.044 possible stochastic outcomes for each midpoint characterization factor and the ECI/MKI values for each element separately. Moreover, the tool calculated these values for both manufacturing and construction, operation, and end-of-life separately and summed up for the total environmental impact score. Thus, implementing this tool would mean that only even one user could produce a representative and elaborate environmental impact score estimation at an early design phase. Additionally, a detailed report is documented in Excel; thus, the results can be evaluated without using the BIM environment. This helps decision-makers and project managers easily access the environmental impact data and manage the project from this perspective. However, note that the raw data in the Excel sheet requires some knowledge of sustainability and LCA. Additionally, the outcome presented in the Excel sheet could also be helpful to the LCA experts to check and compare their finalized LCA calculation results, thus, avoiding any outstanding human errors. A section of the Excel sheet of the raw results is presented in Table 9, and a section of minimum, mean, and maximum values are collected in Table 10.

Table 9 - Fraction of the elaborate data pool of the EI tool

	Impact category	Unit	Raw results:			
Foundation	001. abiotic depletion, non-fuel (AD)	kg Sb eq	1696,51	3565,56	1262,98	2566,22
	002. abiotic depletion, fuel (AD)	kg Sb eq	139168,54	115429,05	79285,59	132415,00
	004. global warming (GWP)	kg CO2 eq	33070208,68	43989395,60	409207,98	39749931,59
	005. ozone layer depletion (ODP)	kg CFC-11 eq	2,33	1,92	1,91	1,89
	006. photochemical oxidation (POCP)	kg C2H4	10681,00	6552,01	8954,97	12667,51
	007. acidification (AP)	kg SO2 eq	88654,45	86615,61	72261,08	113490,75
	…					

Table 10 - Fraction of the minimum, mean, and maximum values of the outcome of the EI tool

	Impact category	Unit	EI_total - Average	EI_total - Min	EI_total - Max
Foundation	001. abiotic depletion, non-fuel (AD)	kg Sb eq	1212,43	0,02	4061,63
	002. abiotic depletion, fuel (AD)	kg Sb eq	72289,86	70,62	212431,12
	004. global warming (GWP)	kg CO2 eq	18896781,29	11464,26	58823378,18
	005. ozone layer depletion (ODP)	kg CFC-11 eq	1,08	0,00	2,99
	006. photochemical oxidation (POCP)	kg C2H4	5846,63	3,51	14414,17
	007. acidification (AP)	kg SO2 eq	54096,17	27,25	157519,35
	…				

Additionally, the Excel sheet produces histograms and boxplots based on the calculated outcomes for each element and environmental impact categories. Through graphical visualization in the documentation in Excel, the tool aims to provide additional insights into the potential ranges of environmental impacts and emphasizes potential hazards when the ranges are too high, or there are unexpected minimum or maximum values lying outside the 50% regime on the box plots. The graphs of global warming potential and ECI/MKI are presented for the environmental impacts of the main components in Appendix A; an example is shown in Figure 9.

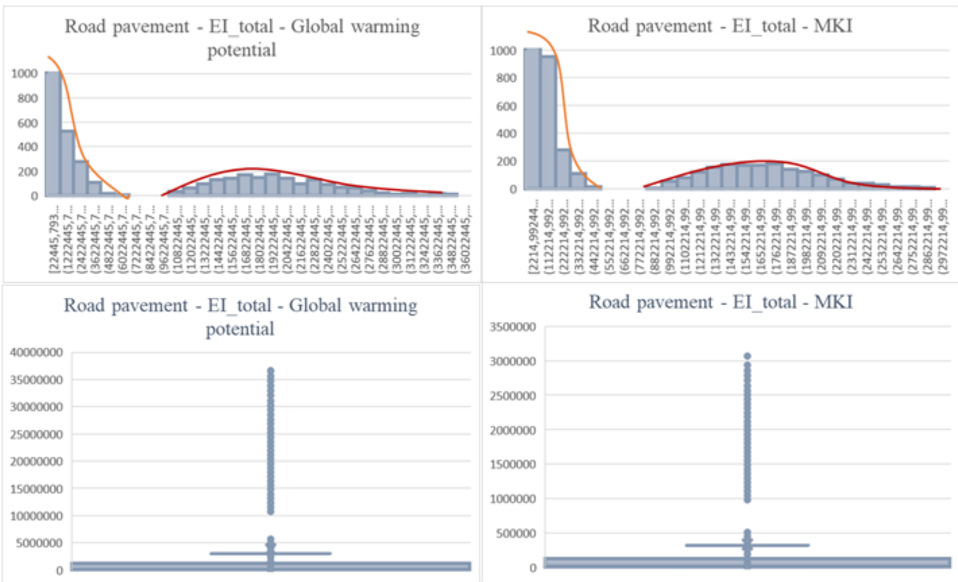

Figure 9 - Bell curves and box plots of the stochastic outcomes for CO2 emission and MKI (orange bell curve: asphalt, red bell curve: concrete)

Note that the graphs with the bell curves and box plots show the overall potential outcomes of the main components, therefore, including all material variations due to considering the related parameter uncertainties. Therefore, it is clear from the graphs that each bell curve belongs to a group of materials or even can be seen the different types of materials, for instance, the prefabricated concrete, reinforced concrete, and concrete groups themselves for the strip, sidewalk, berm element group (see in Appendix A). Therefore, the different bell curves associated with the different materials are the following:

- Dark red curves: for all types and qualities of concrete;
- Blue curves: for different qualities of steel;
- Orange curves: for different qualities of asphalt;
- Green curves: for different qualities of timber.

Next, the results are documented in the Revit model through heatmap color coding, as described in Section 4.7. The representation of this visualization is presented in Figure 10 (and enlarged in Appendix B) for both the environmental impacts of manufacturing and construction (EI_MC), operation (EI_O), and end-of-life (EI_EOL) separately and in total (EI_total).

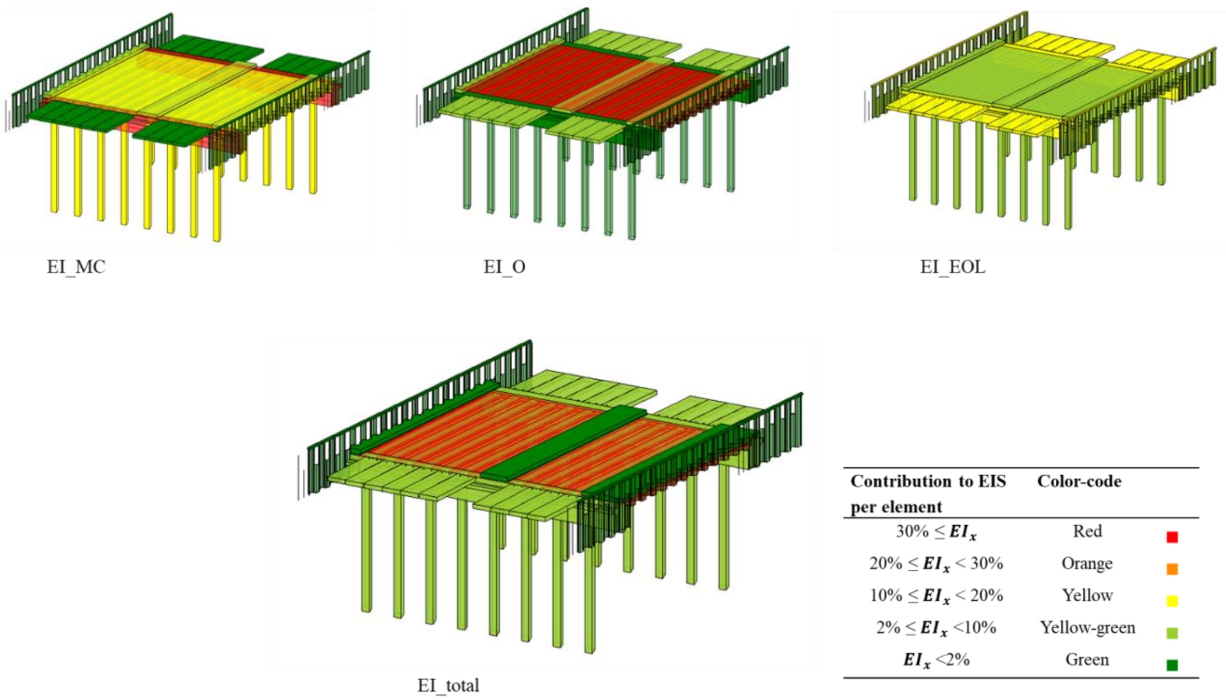

Figure 10 – Visualization of the mean ECI/MKI value per element for manufacturing and construction (EI_MC), operation (EI_O), end-of-life (EI_EOL), and in total (EI_total)

As expected, the concrete components have a more significant environmental impact in the manufacturing and construction phase partially due to these elements' significant volumes. The least influential elements are the sheet pile railing with the PVR cover and the transition plates, partially due to their low volumes. Moreover, the bridge deck construction layers with supporting beams and abutments are visibly transparent, meaning they are still very uncertain at this project stage. At the same time, note that the sheet pile railing with the PVR covers and the transition plates are already definite. During the operation phase, the construction elements most exposed to weather and use naturally have the most significant environmental impacts as these elements need frequent maintenance and replacement. The asphalt layer of the road and cycling pavements have a remarkable environmental impact, while some maintenances are required for the transition plates, strip, berm, and sidewalk structures. Most components are transparent as their materials, and the corresponding maintenance is uncertain. Lastly, the end-of-life stage of the bridge asset is not significant from an environmental perspective as a great percentage of the concrete, steel, and asphalt components are recyclable, and their recycling options and possibilities are relatively straightforward. Overall, asphalt pavements have the most significant environmental impact, followed by abutments, transition plates, pile foundations, and beam structures. The least significant elements throughout all project phases are the sheet pile railing with the PVR covers.

The contribution to the overall score of Global Warming Potential and ECI/MKI is also visualized in a pie diagram (Figure 11). The contribution of the elements has the same percentages for both categories; thus, only one is shown. As can be observed from the graph, concrete elements with great volumes significantly contribute to the total environmental impacts. The bridge deck (52%) is the most significant element from an environmental perspective, as it has a great volume of concrete. Additional concrete components that are influential are the transition plates (12%), the strip/ sidewalk/ berm (12%), the foundation (9%), and the abutment (7%). Next to these, asphalt pavements (4%) and supporting beams (4%) have some contribution to the environmental impacts. Therefore, when experts try to improve the project's overall environmental impact, they should focus on the elements made from concrete and specifically on the bridge deck.

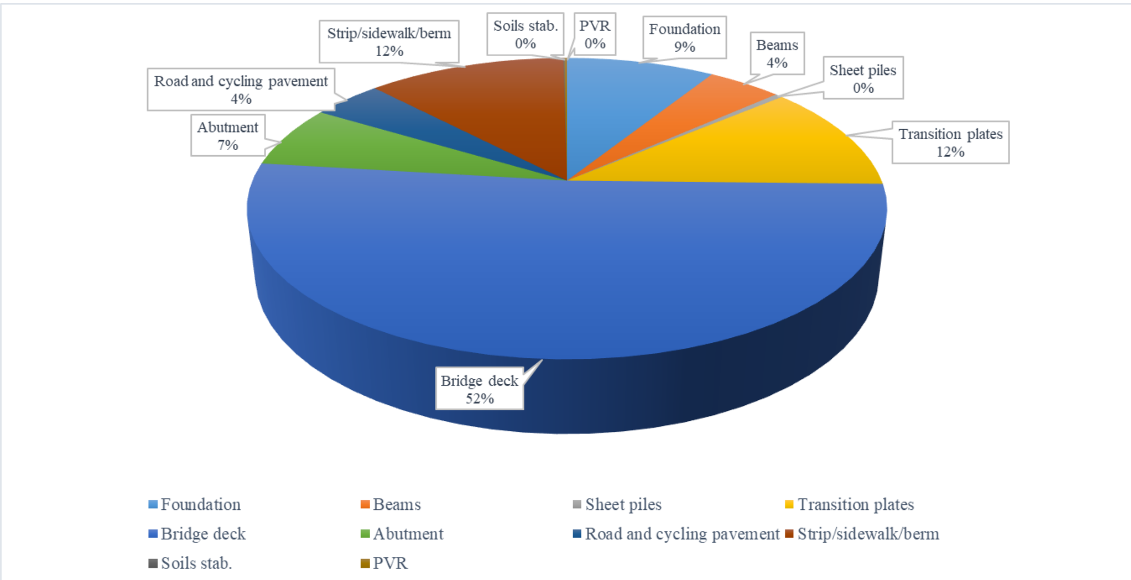

Figure 11 - Contribution of each element to the overall Environmental Cost Indicator (or MKI)

Lastly, the tool is tested through preliminary, final, and construction designs of the above-described bridge asset. The goal was to test whether the tool could be used automatically in different levels of detail designs and to evaluate the potential limitations. It is concluded that the tool can be automatically used in more detailed designs; however, manual adjustments are still necessary. These are primarily reflected in added or entirely replaced elements and their associated parameters. This limitation occurs due to the extraction method of a specific group of elements (Dynamo node of '*Select Model Elements*'). Additionally, the bridge asset with different detail levels is used to set the outcome ranges of the results from the preliminary stages to the final ones. This then indicates the reliability of the estimation of the tool at an early design stage as the resulting ranges narrow down in line with the initial expectations. The results are compared based on the cumulative mean score of the Global Warming Potential [kg CO2 eq.] and the Environmental Cost Indicator [euro/infrastructure asset]. The values are presented in Figure 12 and Figure 13.

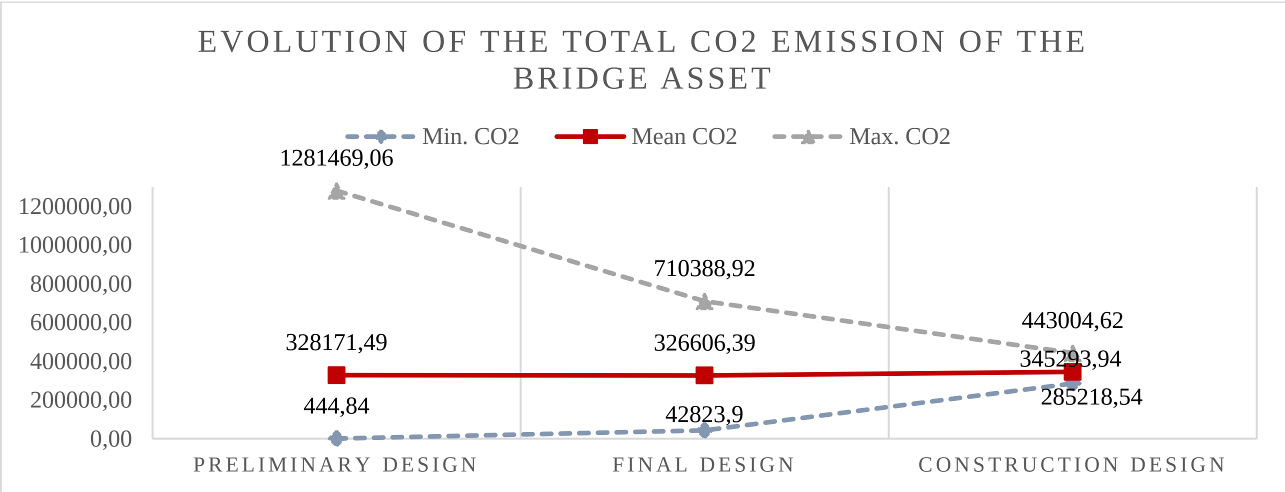

Figure 12 - Evolution of the total CO2 emission of the bridge asset

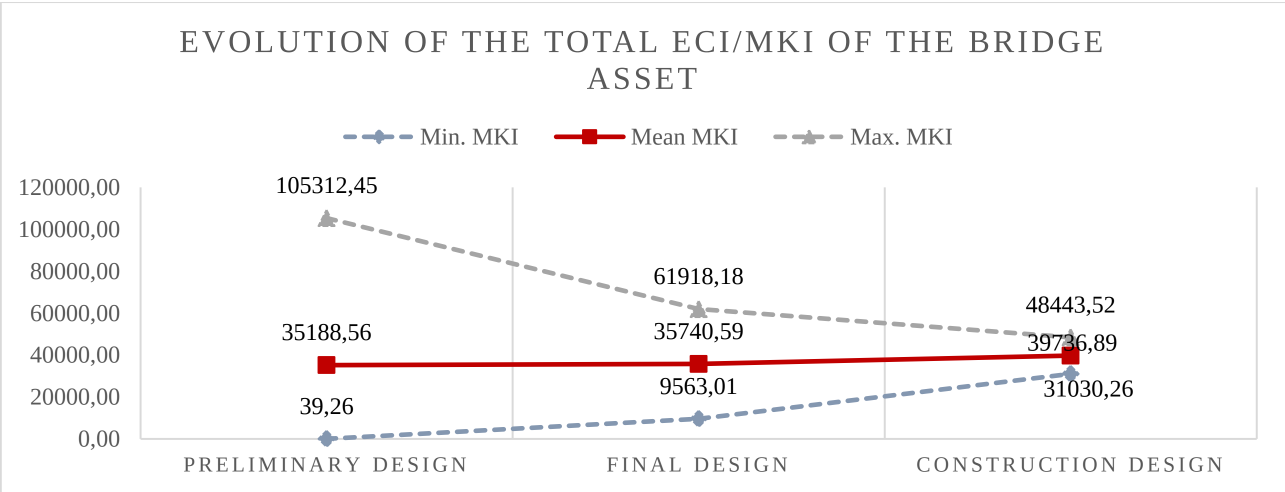

Figure 13 - Evolution of the total ECI/MKI of the bridge asset

Note that the uncertainty ranges or 'boundaries' of maximum and minimum values are narrowing down in accordance with the more information that is available and known about the bridge asset. These values and figures are also used to validate the developed tool, which is further discussed in section 5.4.

5.4 Verification and validation of the results

This research aimed to provide a BIM-based LCA framework that incorporates various types of uncertainties at an early design stage. Consequently, the goal and scope are to present a solution that continuously evaluates the environmental impacts of an infrastructure asset with bi-directional data exchange between the design and LCA software packages to provide immediate feedback for users. Therefore, the developed framework must be evaluated through:

1) the comparison of the current system of obtaining the environmental impact scores outcome with the results obtained by the framework;
2) the time duration of the overall processes;
3) the user experience of use, relevance to their work, operation complexity, the extent to incorporate the framework to their daily tasks and activities, and the importance and usefulness of incorporating uncertainties.

5.4.1 Environmental Impact Assessment accuracy

The validation process is executed by comparing the results generated by the developed tool with the environmental impact assessment manually conducted in SimaPro. The manual calculation is carried out in a deterministic manner where all assumptions are made based on the assisting LCA expert's experience and expert judgment. The baseline environmental impact and ECI/MKI scores are determined based on the preliminary design. Then the deterministically calculated environmental impact is investigated whether it lies within the ranges calculated by the developed tool. The ranges and the SimaPro results are listed in Table 11, investigating whether the manually calculated environmental impacts fall within the ranges at each impact category.

Table 11 - Investigation of SimaPro EIS lies within the tool's calculated ranges

	Unit	Min EIS tool - project	Max EIS tool - project	SimaPro EIS	SimaPro EIS within interval*
001. abiotic depletion, non-fuel (AD)	kg Sb eq	0,01	80,56	1,77	Yes
002. abiotic depletion, fuel (AD)	kg Sb eq	2,88	4242,15	2048,59	Yes
004. global warming (GWP)	kg CO2 eq	466,40	1173859,08	324209,71	Yes
005. ozone layer depletion (ODP)	kg CFC-11 eq	0,00	0,06	0,02	Yes
006. photochemical oxidation (POCP)	kg C2H4	0,29	488,13	417,27	Yes
007. acidification (AP)	kg SO2 eq	1,48	3157,27	1223,15	Yes
008. eutrophication (EP)	kg PO4 eq	0,23	530,17	185,92	Yes

009. human toxicity (HT)	kg 1,4-DB eq	161,62	211535,19	208045,40	Yes
010. Ecotoxicity, fresh water (FAETP)	kg 1,4-DB eq	2,96	144653,40	1769,58	Yes
012. Ecotoxicity, marine water (MAETP)	kg 1,4-DB eq	8177,93	18983945,46	5663284,13	Yes
014. Ecotoxicity, terrestrial (TETP)	kg 1,4-DB eq	0,69	64185,08	858,59	Yes
101. Energy, primary, renewable (MJ)	MJ	218,14	487726,31	164682,75	Yes
102. Energy, primary, non-renewable (MJ)	MJ	5625,50	8526456,00	3513053,51	Yes
104. Water, freshwater use (m3)	m3	3,11	9470,76	2448,02	Yes
106. Waste, hazardous (kg)	kg	0,02	29,16	24,97	Yes
105. Waste, non-hazardous (kg)	kg	209,00	318762,28	58270,95	Yes
107. Waste, radioactive (kg)	kg	0,01	35,05	5,84	Yes
ECI/MKI	Euro	46,81	95753,40	43334,59	Yes

Additionally, the baseline ECI/MKI scores are investigated whether they stay within the calculated ranges, also considering the final and construction design models. Here, the baseline ECI/MKI score is fitted into the evolution graphs, and these are presented in Figure 14 and Figure 15. As can be observed from the graphs, the baseline environmental impact scores stay between the ranges determined by the stochastic BIM-based environmental impact assessment tool at each design stage. Note that this investigation is sampled for the impact categories of Global Warming Potential and Environment Cost Indicator.

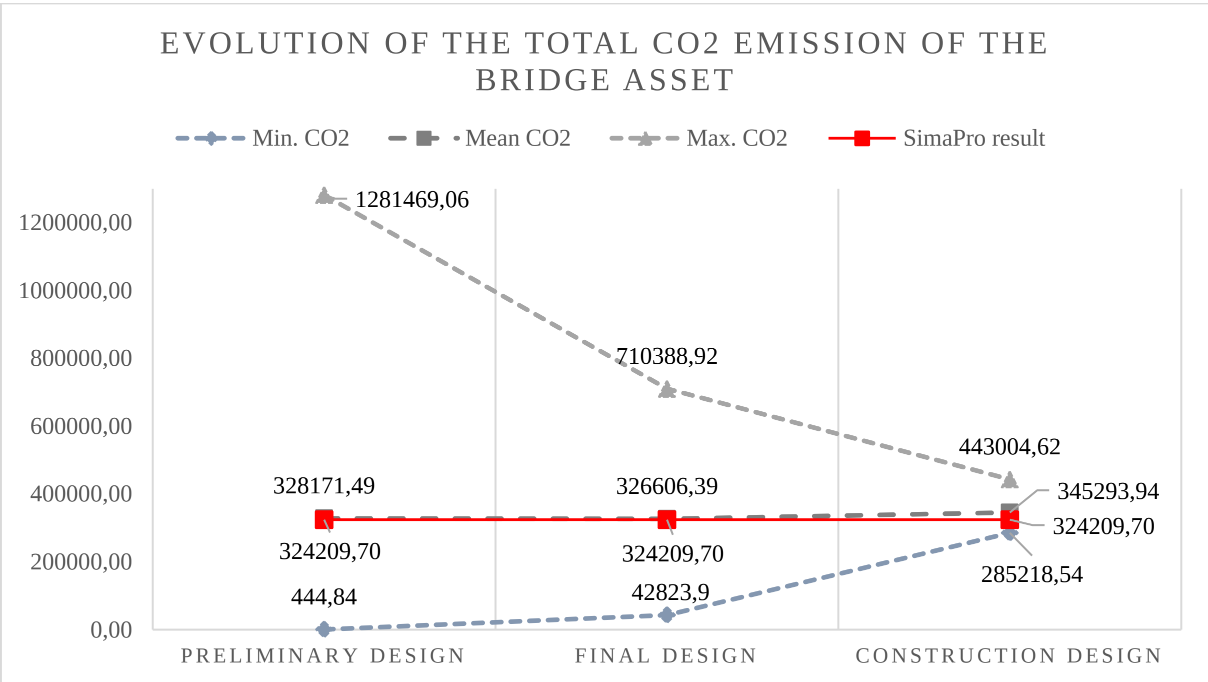

Figure 14 - Investigation of SimaPro EIS lies within the tool's calculated ranges for CO2 emission at each design stage

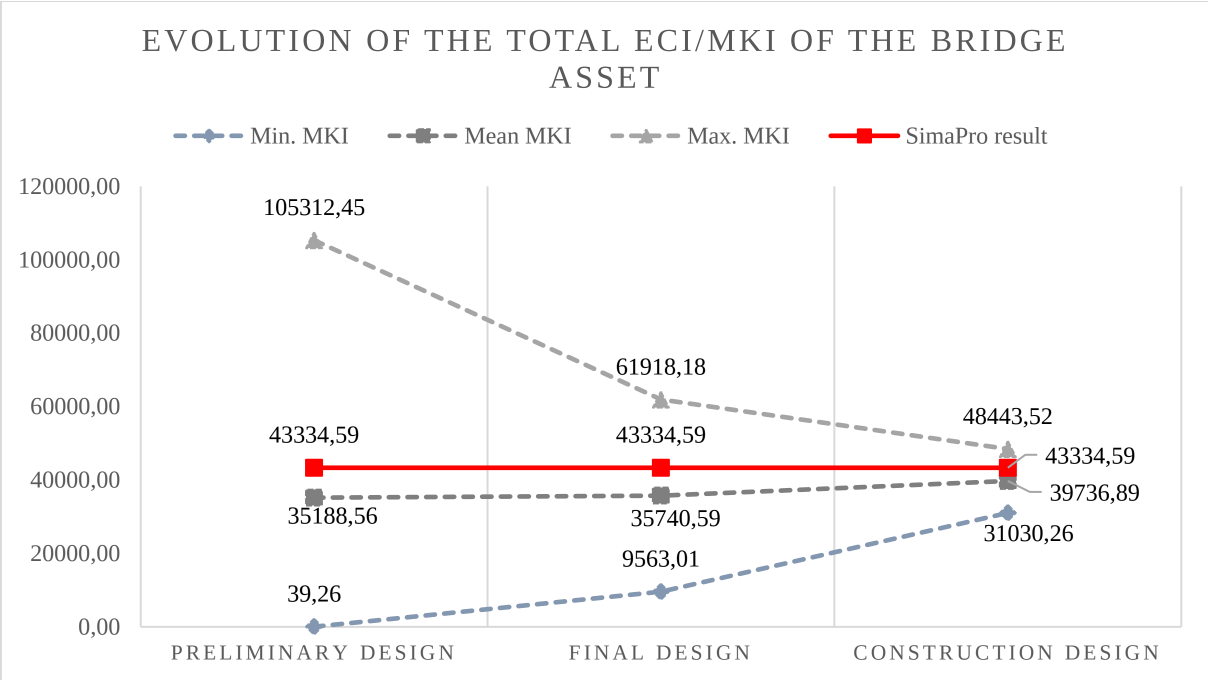

Figure 15 - Investigation of SimaPro EIS lies within the tool's calculated ranges for ECI/MKI at each design stage

5.4.2 Time-saving

One of the main aspects that the framework should support is the time needed to perform the environmental impact assessment process quickly. Therefore, the execution time of the current approach is compared with the time that the framework needs. Additionally, both processes are divided into the time needed for the data collection and the execution time of the rest of the assessment steps. This division was necessary to clarify the differences between these sections further, as the data gathering is usually the most time-consuming aspect of the conventional approach. Regarding the case study presented in this study, there is a need for about 10 to 20 minutes to set up the model and about 5-10 minutes to run, assuming that the historical database and the expert estimation sheet are up-to-date and availble. Setting up the model includes the connection between the tool and the external databases and the relation of the Revit elements to the Dynamo script. Additionally, note that the technological resources (larger memory capacity for computing) can significantly influence the run time to speed up the process further.

In comparison, the data-gathering process for the conventional approach is significantly more extensive, and it is estimated to be around 1 to 3 working days by LCA experts at the company. Additionally, the execution of the further steps of the environmental impact assessment takes about 2 to 6 hours. Note that these time intervals and estimations are related to similar projects of this size, and naturally, these execution time durations greatly depend on the size of the analyzed project.

In summary, the proposed framework can significantly reduce the time required when comparing the data collection process and the assessment time. Nevertheless, each process requires a certain degree of understanding and expertise to use correctly.

5.4.3 User experience and usefulness

To further validate and prove the expedience of the developed framework, a workshop is held among experts at Witteveen+Bos. The workshop is organized for experts with experience in at least one of the fields of infrastructure design, management, engineering, BIM coordination of infrastructure projects, or sustainability. This workshop aimed to investigate to what extent the developed framework and tool is useful to them, how easily it could be incorporated into their daily tasks, whether it contributes to a more sustainable design process compared to the conventional approach, and to what extent incorporating uncertainties is beneficial. The workshop started with a short presentation on the project bases, goals, and boundary conditions; then, the developed environmental impact framework and the tool were demonstrated to the audience; lastly, the results were shown and explained. In the end, a discussion was conducted where experts could ask additional questions regarding the project.

The workshop is summarized via a questionnaire distributed among the experts after the workshop. The questionnaire targeted the tool's relevance, functionality and applicability, scalability, sustainability perseverance, and importance of uncertainty reflected in the outcome. In general, experts believe that the tool could be handy in estimating the environmental impact of infrastructure projects, improve the sustainability of not only the current but more projects in general, and could be easily incorporated into their everyday tasks. Furthermore, they believe that the proposed tool could be easily used in different construction domains and can be upscaled to more than just one discipline of sustainability. However, the experts' opinion is distributed on the tool's ease of use and interpretation of the results. This is understandable, as there is still a gap between disciplines, meaning that for designers, engineers, or BIM coordinators, the use of the tool would not be complicated, but at the same time, the interpretation of the result would be problematic. Naturally, sustainability experts have the issue the other way around. That is why the tool is aimed to support designers and engage them to design with sustainability aspects in mind, thus, subjecting them only to the visualization in the BIM environment, while the overall outcome should be understood by managers and LCA experts who have the decision-making power. Lastly, the importance of uncertainty and its incorporation is paramount among experts as they believe the tool could efficiently contribute to the uncertainty and sensitivity analysis process along the environmental impact range determinations.

Experts participating in the questionnaire had the option to rate the above-mentionned qualities of the tool from 1 to 5, where 1 was the lowest score and 5 was the highest option. In total 42 experts participated in the questionnaire, and their responses are calculated in average scores to be able to compare the conventional EIA with the developed EIA method. A summary of the questionnaire results are presented in Table 12 and visualized in the graph in Figure 16.

Table 12 – Average results of the expert questionnaire

	Current system	Developed framework/tool
Evaluation of the design	3	3,81
Improvement of the design	2,636	3,545
Easy to use	2,81	3,364
Time	2,909	3,364
Upscaling to another project	3,182	3,636
Upscaling for more sustainability disciplines	2,909	3,545
Enhances sustainability consciousness	2,273	3,909
Evaluation of uncertainties	2	4
Evaluation time of uncertainties	1,333	4,33
Conduction of sensitivity analysis	2	4,33
Conduction time of sensitivity analysis	1,667	3,33
Accuracy at an early design	2	3,33
Identifying focus points for improvement	2,33	4

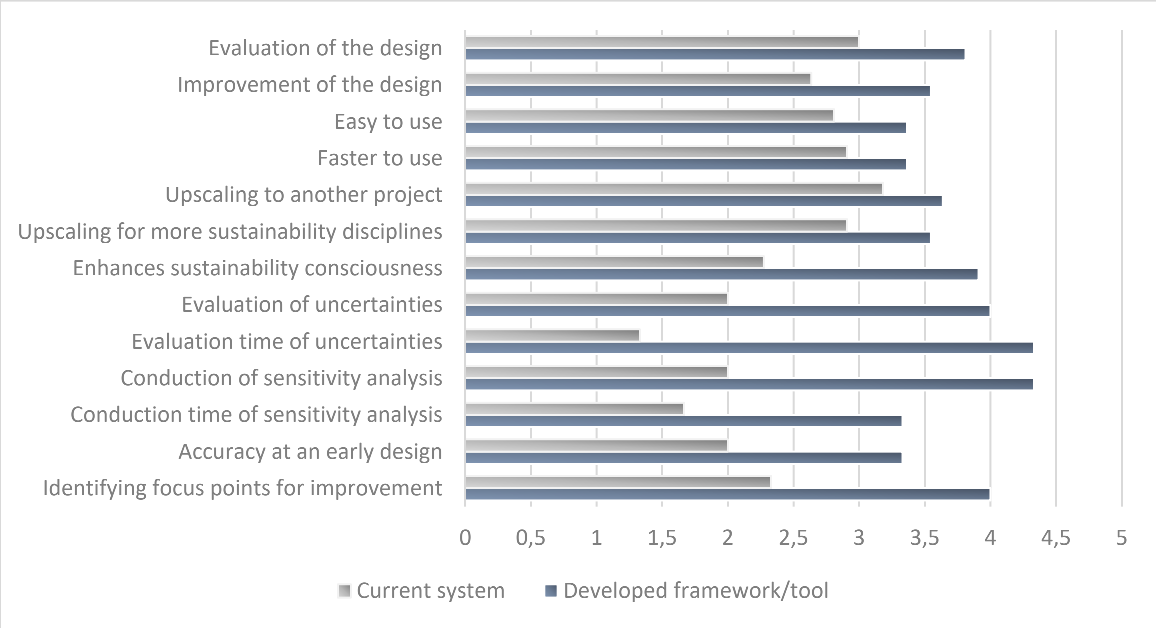

Figure 16 - Visualization of the outcome of the questionnaire

In general, most experts thought that the developed method and tool improved all the disciplines listed in the questionnaire. Notably, the most significant improvements can be seen in the answers related to uncertainty incorporation and their reflection in the resulting ranges. Additionally, one group of LCA experts responsible for innovative solutions and bringing different disciplines closer were highly enthusiastic and interested in the tool. Therefore, the workshop was presented on two additional occasions, where further approaches on synthesizing and financing the presented ideas with the currently used semi-manual approach are discussed.

During the workshop discussion, a few remaining issues were identified. Most of these were related to the extreme values of the generated ranges. Currently, the framework and, thus, the tool try to capture a great range of uncertainties as input. However, the random attribute selection process makes the extremely low environmental impact scores unreasonable due to nonsense scenarios or lack of structural soundness. In contrast, the exceptionally high environmental impact score is not logical due to high resource investment needs. Therefore, a control step in the future must be implemented in the tool to avoid these unrealistic outcomes.

6 Discussion and recommendations

The presented research contributes to the existing knowledge base by proposing a BIM-based LCA framework that incorporates each type of uncertainty for the infrastructure sector of the construction industry. Additionally, the framework can continuously evaluate the environmental impacts from an early design stage to the finalized project without using external LCA software packages. A categorical structure is presented that assists the two-directional data flow between different EIA databases and the design platform. Moreover, the framework explores the possibility of incorporating the EIA data within the BIM environment. Its successful implementation in the corresponding tool proves the viability of this solution, reduces interoperability issues between software packages, and limits human errors made during the execution process. Lastly, the framework provides immediate feedback to users in a detailed report with figures and graphs to enhance the interpretation of the results and in color-coded visualization in the BIM environment. The developed framework is tested on an infrastructure case study to evaluate its practicability and flexibility in the preliminary, final, and construction design phases.

Even though the presented framework is very effective in determining the environmental impact ranges of an infrastructure asset in a considerably short time, it has a number of dependencies and limitations at its current stage. First, the framework significantly depends on the input parameters, their certainty and completeness, the associated historical database that needs to be updated, and the plug-in applicability of EIA databases. In theory, it would be possible to connect any EIA database directly to the framework; however, this option is legally not possible at the moment (there is no right for the company to access the entire database for its raw data). Regarding the historical database, a more exhaustive data gathering is proposed, and the upkeep of it is inevitable. This could be obtained by requiring experts to document all the attribute choices and quantities in future projects and use this internal database within the framework.

Next, the framework simplifies the iterative process of designing an infrastructure asset, meaning that it neglects to review all randomly selected combinations of attributes and whether they are viable from a sustainability perspective and structural integrity. Therefore, a control step is required to develop the tool further for plausible outcomes. This could be executed along with simplified sustainability checks and structural calculations to narrow the lower boundaries of the range of the outcome and integrate cost aspects into the framework to discard all the illogically high investment needs.

Additionally, currently, there is a need for an engineer who could make the connections between the Revit model and the Dynamo script and link all the external databases to the model itself. In the future, a more straightforward user interface should be developed where users can link all the required databases and choose manual inputs from a dropdown menu more easily and quickly.

Furthermore, the framework is limited to evaluating environmental impacts, but the other domains of sustainability are neglected. This implies that the framework could incorporate economic and social aspects to achieve a comprehensive sustainability assessment in the future.

Lastly, incorporating a wide range of uncertainty as an input within the framework naturally results in an even larger range of outcomes. It must be noted that incorporating uncertainties makes the final scores more accurate; however, going to extremes with uncertain ranges could result in vague and unclear output. Therefore, a balanced and informed selection of ranges is inevitable.

7 Conclusion

Considering the sustainability aspects of a product is more and more relevant nowadays. Therefore, the construction industry should be developed in this field to keep up with the sustainability demand. In this regard, LCA and cost analysis of construction projects are carried out; however, these processes require significant time and effort. Moreover, these assessments could only be executed when all necessary data is available, leaving the sustainability assessment carried out at the end of the construction projects. This, however, limits the decision-making process from a sustainable perspective. Therefore, a method that could swiftly evaluate the project's sustainability at any given project stage could be industry-changing.

Within this study, a framework is developed that satisfies the primary endeavors of environmental impact assessments. It incorporates different types of uncertainties at an early design stage, thus, limiting the expert assumption needed in the assessment process. Furthermore, it is integrated into the design software to engage and navigate designers toward a more sustainable design process. It is demonstrated that the framework could be used in particular project scenarios. However, at the same time, its scope can be easily adjusted for other infrastructure design projects as well as even for other domains of the construction industry. The environmental assessment can be carried out at any project stage in a reasonably short time and provides a good estimation for overall mid- and end-point environmental impact scores that can be used in tendering processes, applying for permits, and other legalization processes.

Future research on the integration of BIM-based LCA, considering the stochastic nature of infrastructure projects throughout the design process, should focus on the followings: (1) include all pillars of sustainability, meaning that include economic and social aspects next to the environmental one, preferably within or linked to the design software to keep the integration of all information in the design interface, (2) working towards a direct connection between the BIM environment and the LCA databases to achieve a robust framework that incorporates all possible parameters available at the market, (3) extend the framework for different LCA scenarios, as the location of the assets, different boundary conditions, environmental impact assessment methodologies, Etc. Additionally, build an appropriate control step that eliminates all the impossible scenarios from sustainability, structural integrity, and economic perspectives. This last issue could be resolved by elevating the framework into a generative simulation or machine learning concept.

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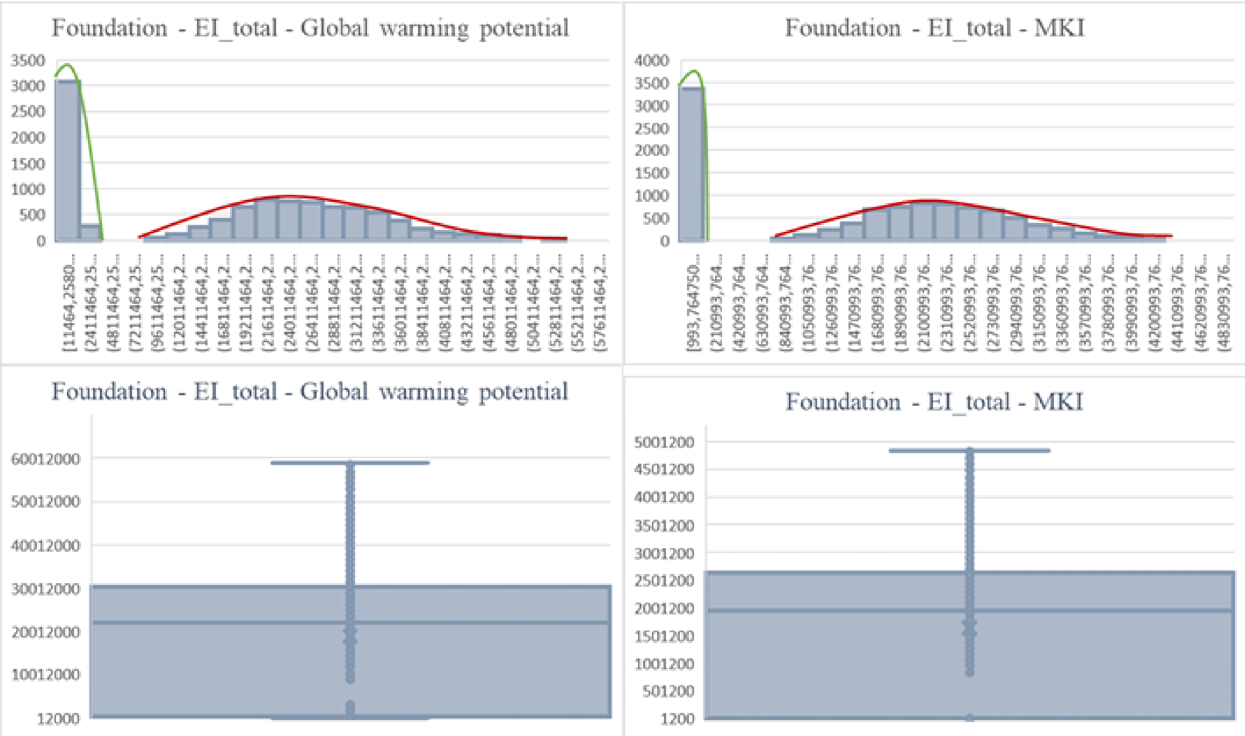
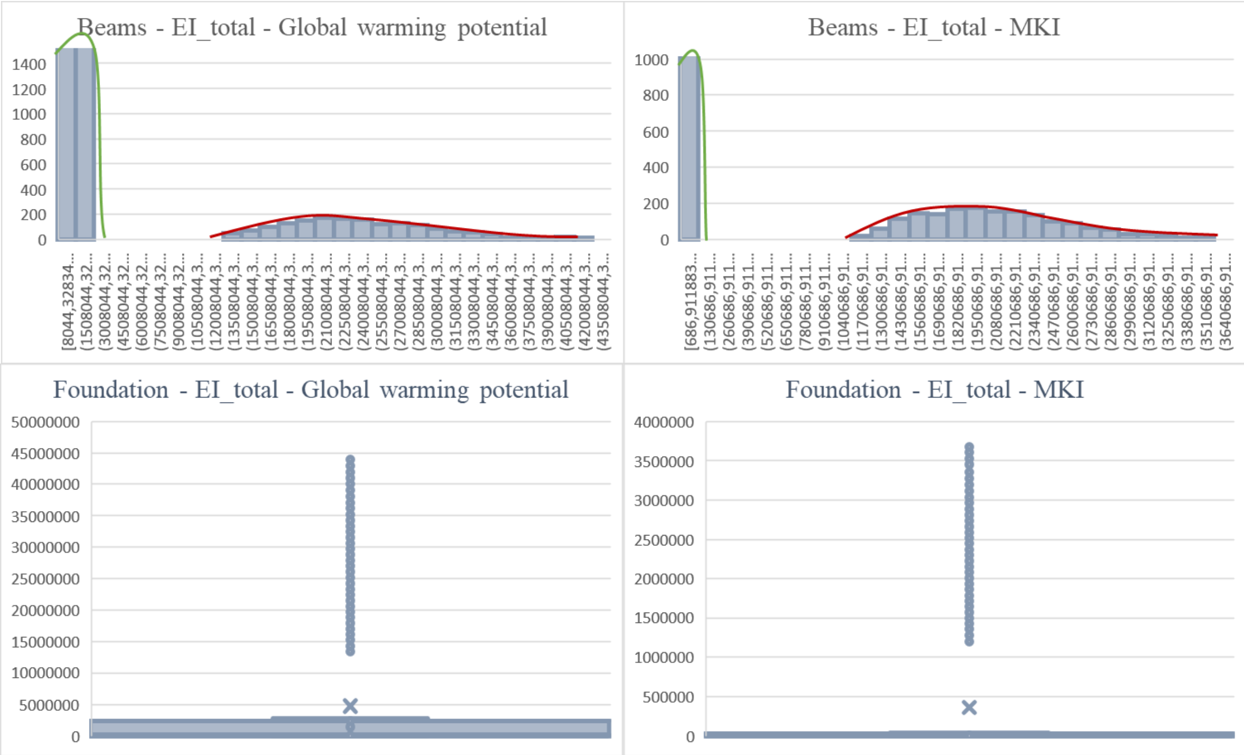
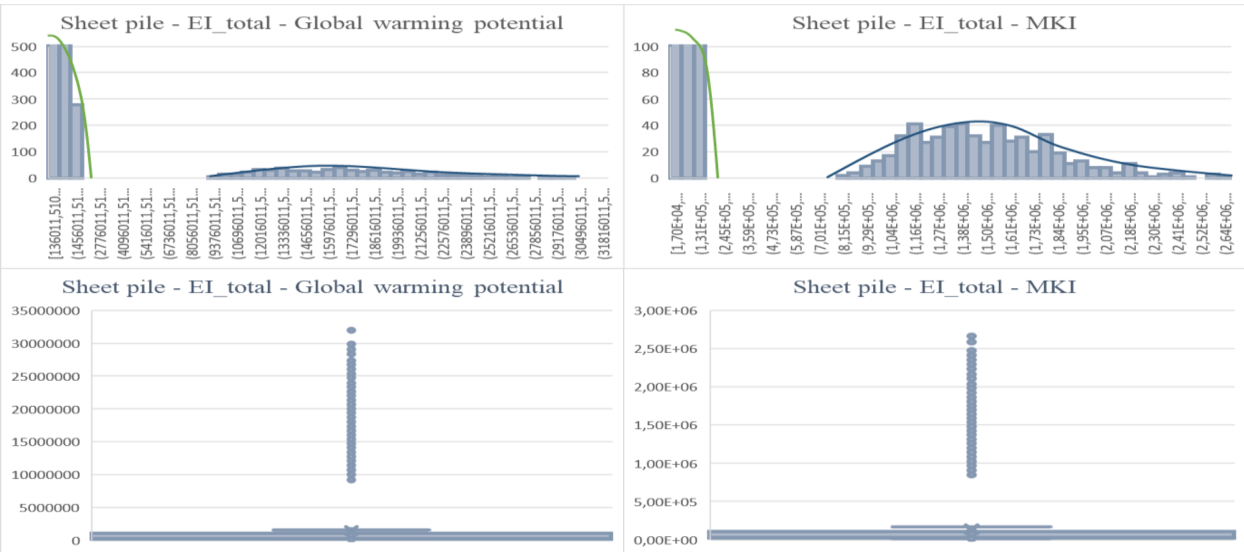
9 Appendix

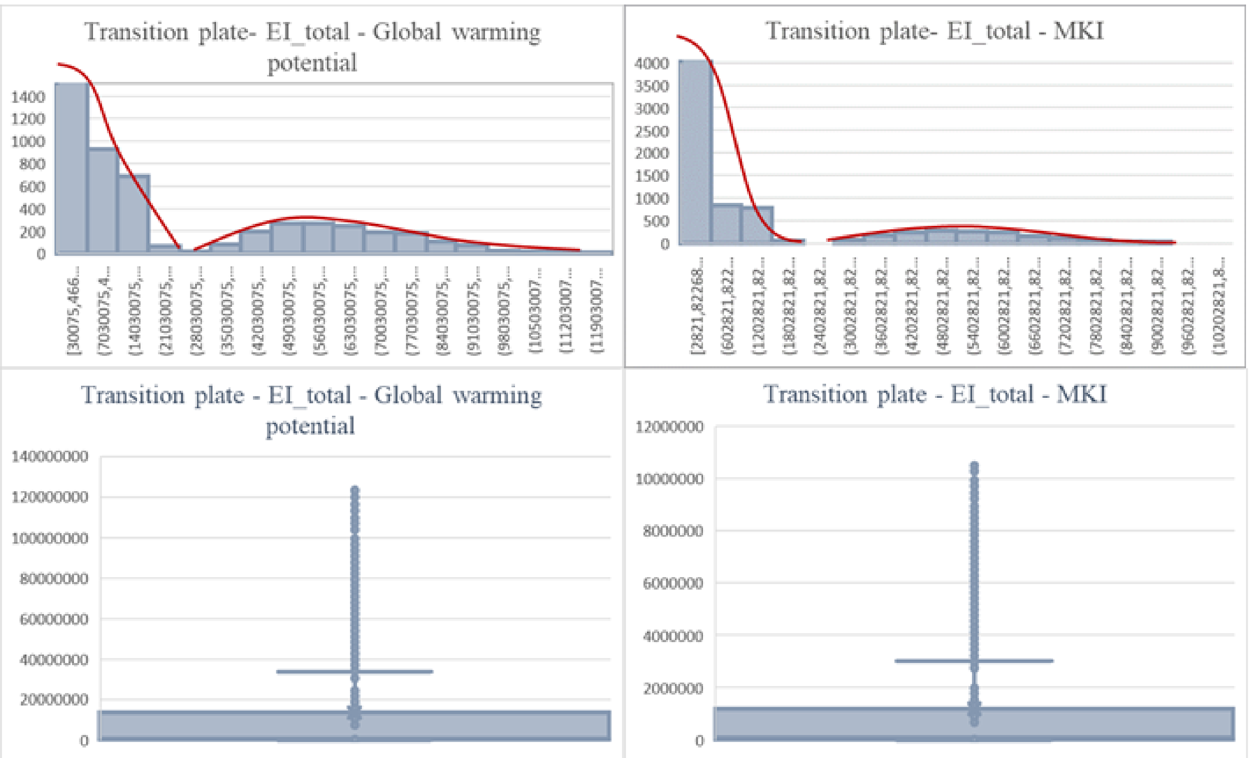
Appendix A – Bell curves and box plots of main infrastructure components for global warming potential and ECI/MKI scores

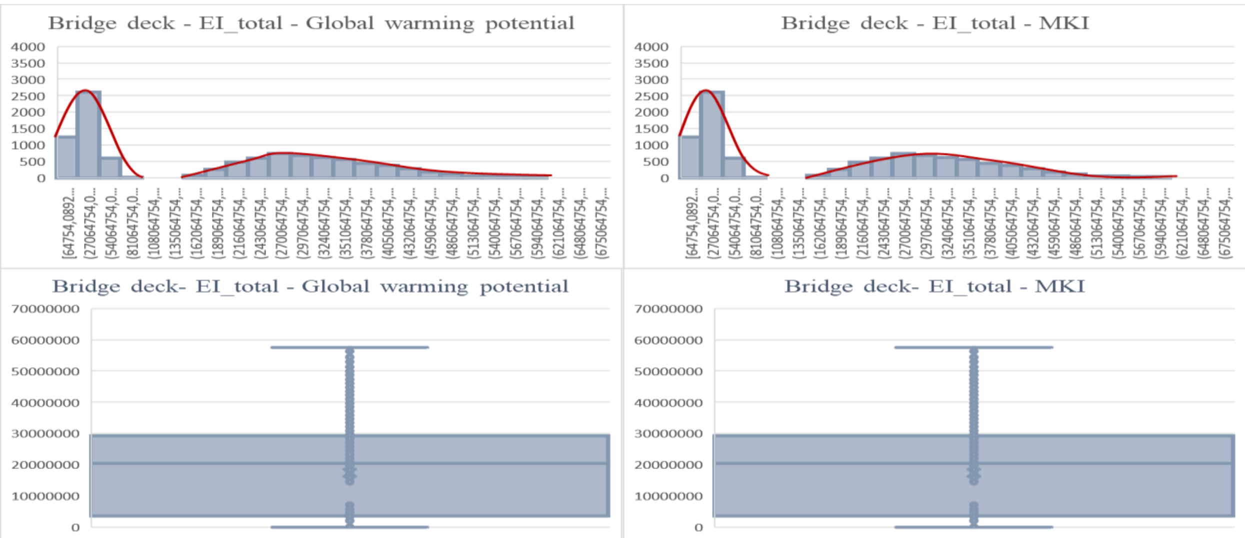
- Dark red curves: for all types and qualities of concrete;
- Blue curves: for different qualities of steel;
- Orange curves: for different qualities of asphalt;
- Green curves: for different qualities of timber.

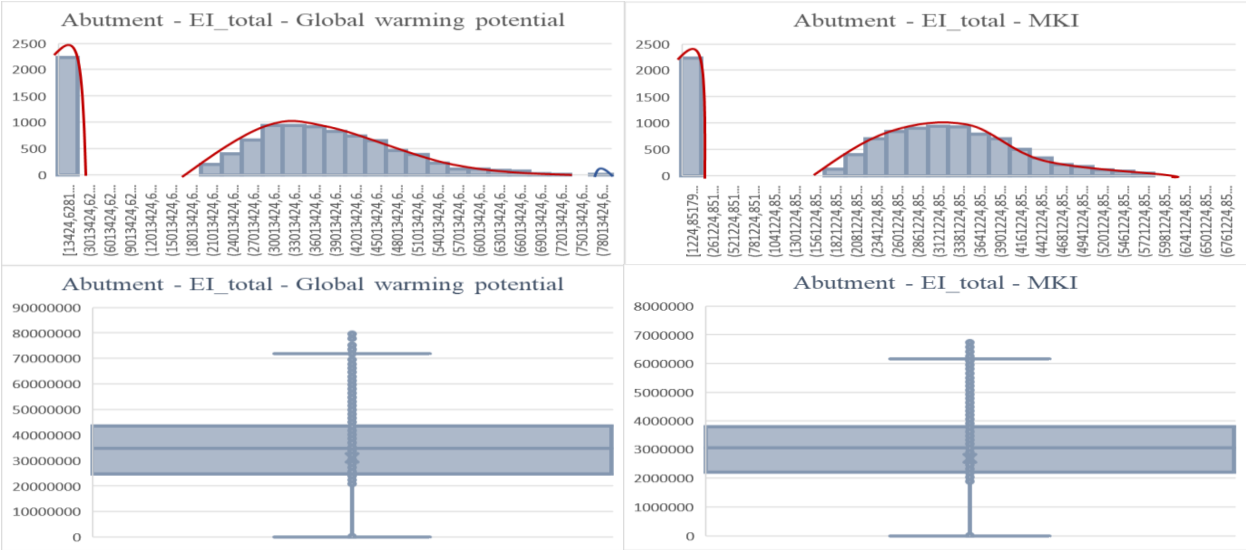


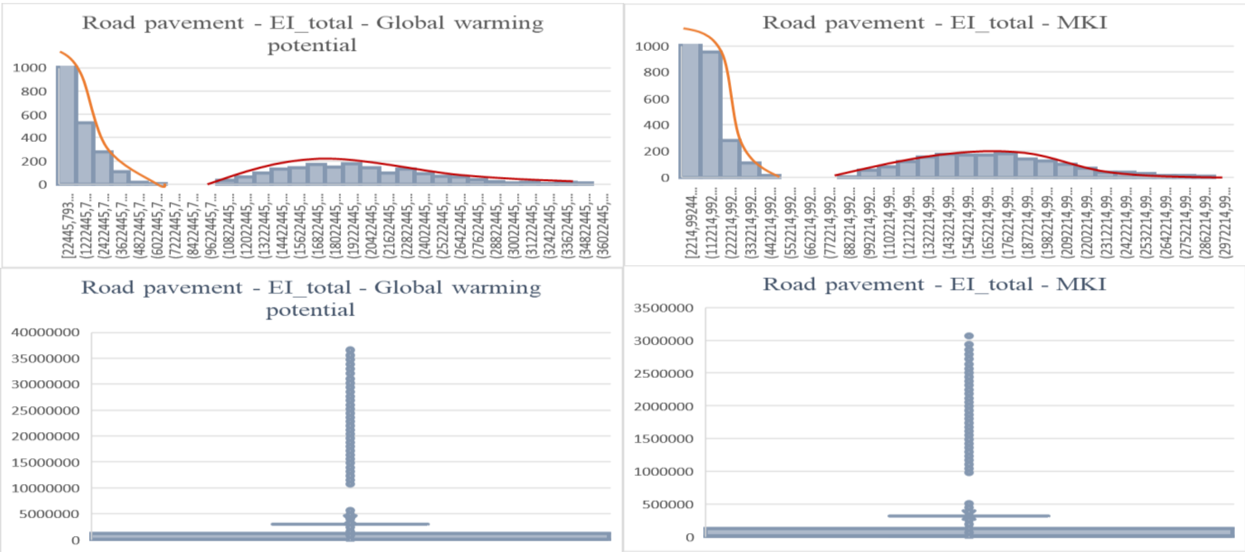

Beams - EI_total - Global warming potential
Beams - EI_total - MKI
Foundation - EI_total - Global warming potential
Foundation - EI_total - MKI

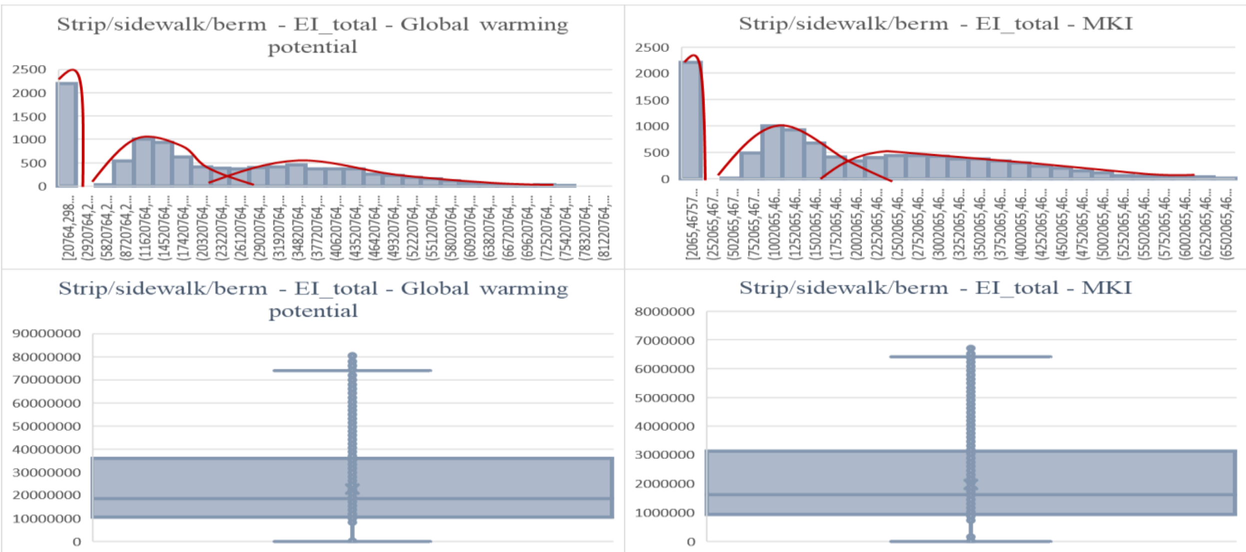

Sheet pile - EI_total - Global warming potential
Sheet pile - EI_total - MKI
Sheet pile - EI_total - Global warming potential
Sheet pile - EI_total - MKI


Transition plate- EI_total - Global warming potential
1400
1200
1000
800
600
400
200
0
Transition plate- EI_total - MKI
4000
3500
3000
2500
2000
1500
1000
500
0
Transition plate - EI_total - Global warming potential
140000000
120000000
100000000
80000000
60000000
40000000
20000000
0
Transition plate - EI_total - MKI
12000000
10000000
8000000
6000000
4000000
2000000
0


Bridge deck - EI_total - Global warming potential
4000
3500
3000
2500
2000
1500
1000
500
0
Bridge deck - EI_total - MKI
Bridge deck- EI_total - Global warming potential
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
Bridge deck- EI_total - MKI

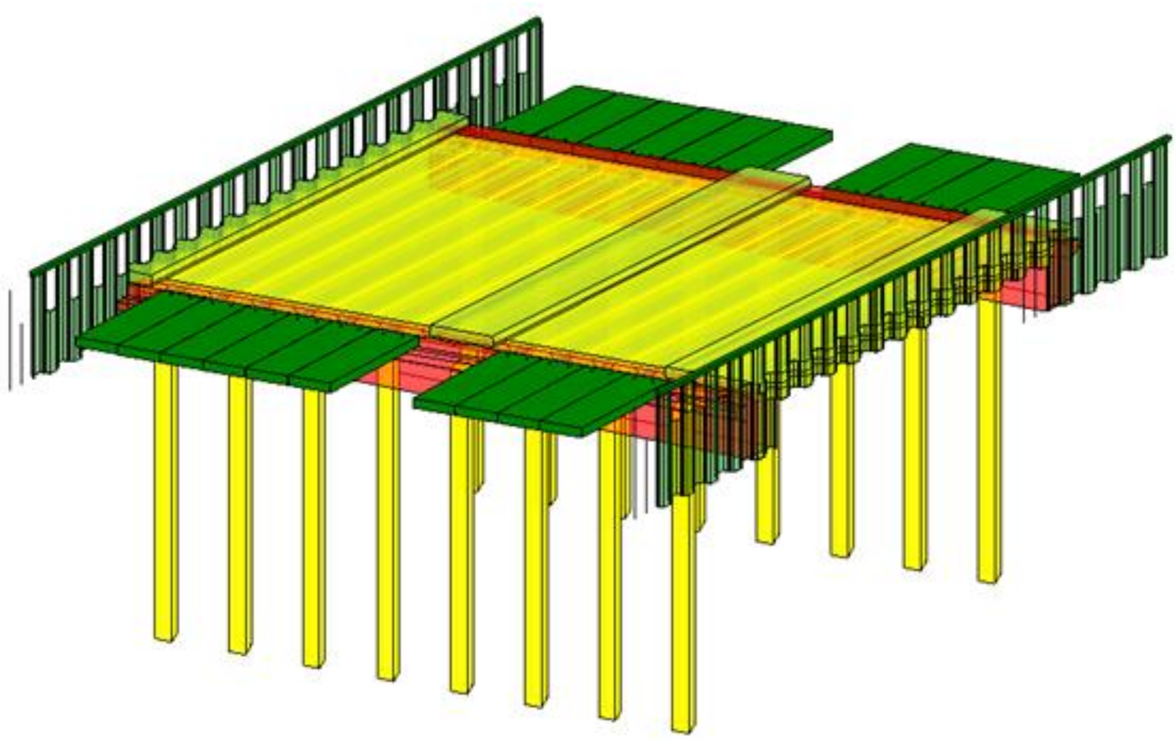

Abutment - EI_total - Global warming potential
2500
2000
1500
1000
500
0
Abutment - EI_total - MKI
2500
2000
1500
1000
500
0
Abutment - EI_total - Global warming potential
90000000
80000000
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
Abutment - EI_total - MKI
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0


Road pavement - EI_total - Global warming potential
1000
800
600
400
200
0
Road pavement - EI_total - MKI
1000
800
600
400
200
0
Road pavement - EI_total - Global warming potential
40000000
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
Road pavement - EI_total - MKI
3500000
3000000
2500000
2000000
1500000
1000000
500000
0

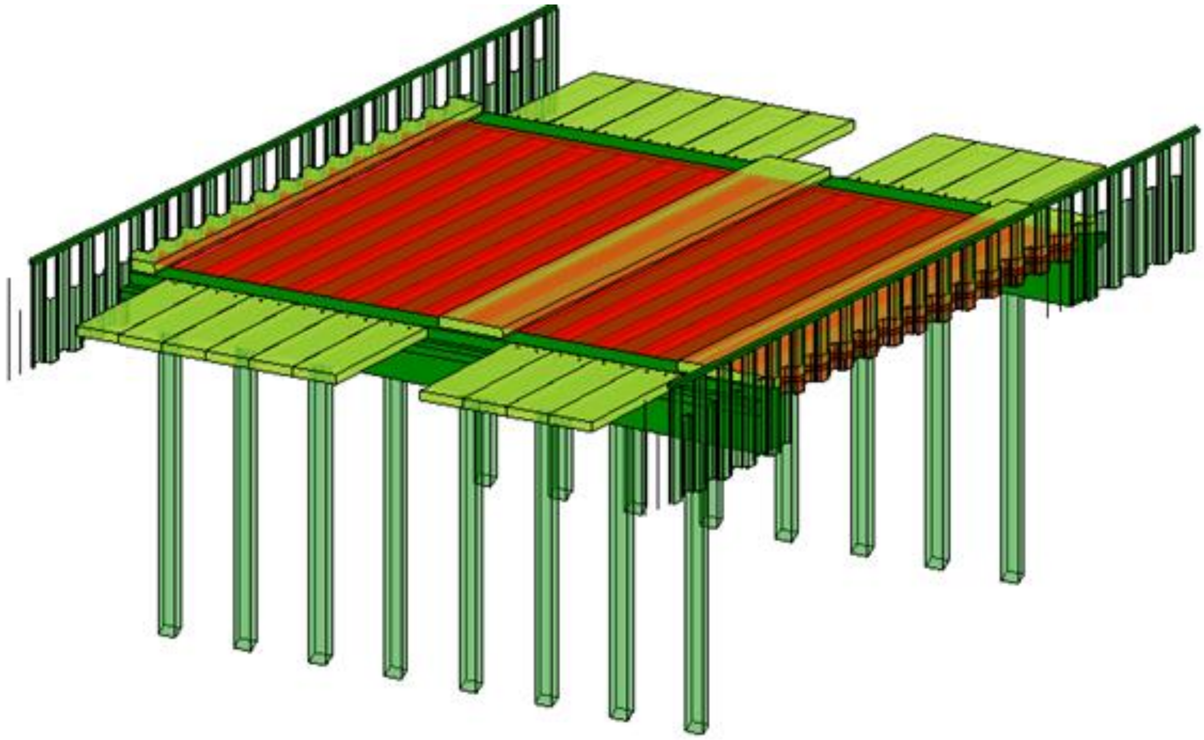

Strip/sidewalk/berm - EI_total - Global warming potential
2500
2000
1500
1000
500
0
Strip/sidewalk/berm - EI_total - MKI
2500
2000
1500
1000
500
0
Strip/sidewalk/berm - EI_total - Global warming potential
90000000
80000000
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
Strip/sidewalk/berm - EI_total - MKI
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0

Appendix B - Visualization of the results in duplicated 3D views in Revit

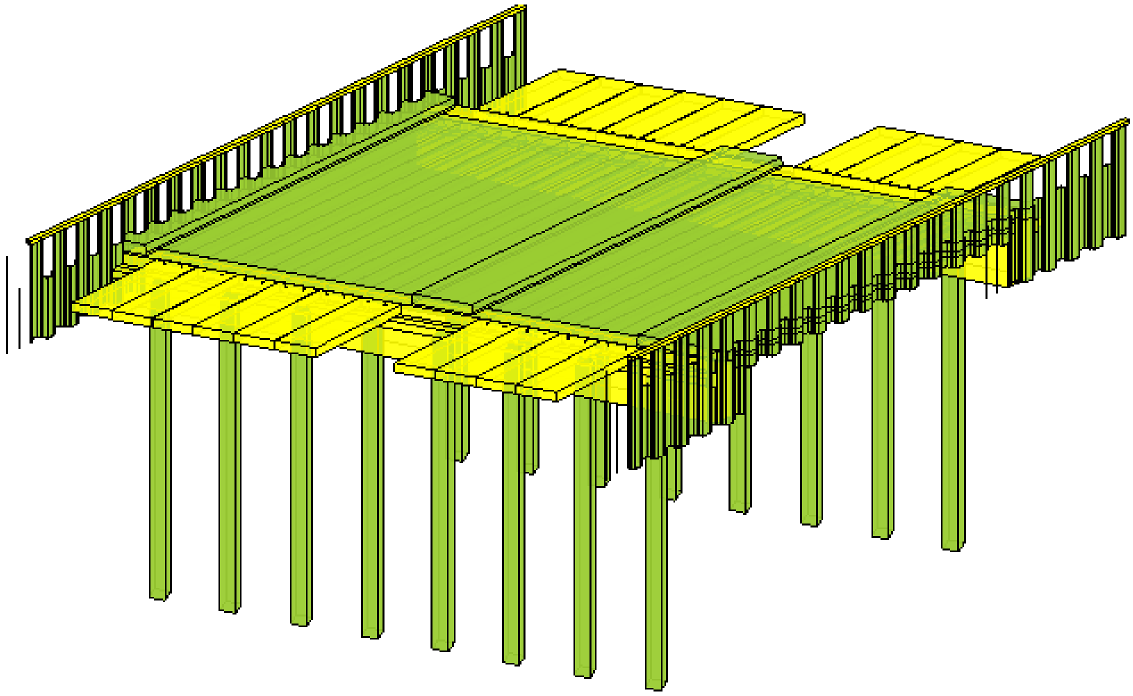
Environmental impacts of **manufacturing and construction** processes (EI_MC):



Environmental impacts of **operation** process (EI_O):



Environmental impacts of **end-of-life** process (EI_EOL):



Environmental impacts of the **total** infrastructure asset (EI_total):