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Building Information Modeling-based Bridge Sustainability Analysis

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Sustainability of infrastructures is acknowledged to be a global problem that requires a complex solution. To implement sustainability practices over the lifecycle of an infrastructure, its entities are to be studied both separately and in conjunction with each other. Bridges are the key elements of transportation infrastructure and their sustainability is not yet paid sufficient attention to. The aim of this thesis is to develop a bridge sustainability rating system and to bring in a Building Information Modeling-based process that supports it. Based on the literature studies, bridge sustainability assessment system was elaborated and suggested to be performed with Industry Foundation Classes data standard. As a result, it was established that the Industry Foundation Classes standard has a perspective to be a platform for the sustainability analysis of a bridge. This final year project can be used as a concept by both environmental and construction professionals to endorse sustainability of a bridge over entire lifecycle.

Keywords	BIM, IFC, bridge, sustainability

Contents

List of Abbreviations

AEC	Architecture, Engineering and Construction (Industry)
BIM	Building Information Modeling
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-aided design
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
LEED v4	Leadership in Energy and Environmental Design, version 4
PDM	Project Delivery Method
SF	Sustainability Factor
TBL	Triple bottom line

1 Introduction

Lately, the business development has been acknowledged to contradict with the economic and social spheres, thereby frequently prioritizing profit and compromising nature protection along with fair treatment of people. As a result, ecosystem pollution emerges, leading to adverse health consequences for both humans and other inhabitants of the environment. At this rate, a large ecological disaster is inevitable. In order to avoid this catastrophe, the very basic principles of business operation need to be reconsidered.

In the end of 20th century, the Brundtland report officially raised the problem of the negative environmental and social impacts caused by businesses. Subsequently, a birth was given to sustainability concept which encompasses a balanced interaction of three spheres: economic, environmental, and social. In other words, while the conventional business model primarily underlines profit, sustainability places importance not only on earnings, but also on the same high concern for both people and environment equally. As a result, a new complex business development model was introduced. In brief, the model underlines the satisfaction of the current social needs, while not compromising the needs of the future generations. Correspondingly, the model implementation requires substantial modifications in every sphere of life.

At the moment, various environmental experts acknowledge the construction industry to be one of the largest contributors to ecological pollution. Its product, built environment, represents everything that surrounds a person in the urban area. The largest objects related to the built environment are buildings and infrastructure, which serve human needs while demanding an immense amount of energy and materials for execution and operation. In recent years, a multiplicity of researchers and experts have proposed a plurality of concepts for sustainability adoption in the construction industry. However, the industry is vastly complex and considered to be one of the most conservative ones. Thereby, construction field professionals commonly recognize that a large gap between theory and its implementation takes place. Building Information Modeling (BIM) may yet promise to be one of the most potent solutions for the acceleration of the promotion of sustainability. BIM includes powerful, information technology-based tools and processes that allow for an early implementation of sustainable strategies during the design phase of a construction project.

While comprising and linking a multiplicity of disciplines and software, BIM encourages a higher level of communication, execution quality, time and costs savings. With its digital modeling and efficient analysis possibilities, BIM has the potential to face the sustainability challenge and to make an optimum decision from a plurality of alternatives.

Unlike the building sector, it is assumed that the sustainability of infrastructure has not yet been studied at a sufficient extent. However, infrastructure commonly covers larger areas of the built environment and, similarly, is substantial to be considered when addressing the sustainability issue. In addition to that, this sector is believed to be more complex than the building industry, as it covers a variety of multi-oriented assets and facilities. In this context, infrastructure sustainability consists of a highly sophisticated set of principles. To achieve valid outcomes in problem-solving, infrastructure is to be examined as a whole in addition to its particular object evaluation. Transportation infrastructure constitutes foundational systems and structures for transporting goods and people. Substantially, its quality and investment demands have a great impact on the local environment, society, and economy.

Bridges are one of the key elements of transportation infrastructure that are meant to provide a path through an obstacle on the route. At the moment, bridge sustainability is assumed to be a high concern subject, as many bridges across the world are reaching their service life limits and, thus, require replacement or renovation. As the extent of the issue is global, inadequate problem management can lead to major environmental consequences, poor infra service quality, and high costs. Similarly to the entire built environment, the implementation of the principles of sustainability may be a beneficial solution. Nevertheless, to this moment, bridge sustainability research accounts for a relatively little amount of data. Infrastructure sustainability assessment systems still focus on a rather wide perspective, while there are almost no agreed criteria on a sustainable bridge. This paper reports a study carried out in an attempt to derive a universal bridge sustainability assessment system. Furthermore, an effort is made to investigate how BIM could efficiently be utilized in sustainable bridge assessment. As a result, sustainable bridge assessment is introduced to act as an effective decision-making tool for supporting sustainability-oriented design, construction, and operation.

Chapter 2 of this thesis provides information about sustainability definition and fundamentals. Chapter 3 describes sustainable built environment principles, as well as concepts for infrastructure and bridges in particular. Chapter 4 includes brief information on BIM tools and standards, the research on bridge sustainability factors (SFs), as well as a description of a prototype for a BIM-based bridge sustainability analysis software prototype. In the end, recommendations are given on the subject, and perspectives and limitations are discussed.

2 Sustainability

2.1 Sustainable Development

In the second half of the 20th century, with the increase in world population and life quality standards, a new problem emerged. In 1987, the Brundtland Report by The World Commission on Environment and Development stated that the unequal distribution and use of the planet's natural resources adversely impacts the environment and human health. To prevent global negative consequences, a new approach to industry and society operation has to be employed. [1.] Governments are to face a complex problem of balancing between economic growth and reasonable utilization of the planet's resources. In other words, a new model of socio-economic development is to be implemented worldwide. Thus, a term “sustainable development” has originated by the Commission: ‘Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs’. [2.]

To a certain extent, unsustainable development has allowed businesses to grow fast. However, it has degraded the environment on a large scale, so that perpetual growth is limited. Thus, sustainable development, as a framework, turns up as the only favorable problem solution. In the long-term, it is beneficial to both society and the environment. [2; 3.] When establishing the World Commission on Environment and Development, General Assembly of the United Nations declared two concepts crucial for sustainable development: first, the welfare of people, economics, and the planet are closely linked; second, sustainable development requires integration and co-operation both locally and globally. [2.]

2.2 Triple Bottom Line

The expression “Triple Bottom Line” (TBL) was first introduced in the 1990s by John Elkington, a co-founder of SustainAbility consultancy and 'a true green business guru'. TBL is a complex accounting framework that evaluates the sustainable performance of a business in three dimensions: social, economic, and environmental. [4; 5.] The idea of business focusing not just on the financial bottom line, but also on social and environmental aspects has originated from the Brundtland Report. However, Elkington has developed it and proposed further practical applications to businesses. [6.] He has referred to BCSD chairman Stephan Schmidheiny, who stated one of the central concepts of the sustainable business: “Sustainability requires that we pay attention to the entire life cycles of our products and to the specific and changing needs of our customers” [7].

Therefore, the “true business guru” has raised the awareness of businesses and customers of responsible company image. Thus, Elkington has become one of the initiators of a corporate responsibility inquiry and a Fair Trade movement. [4.] John Elkington has clearly stated the idea behind the sustainability tool: “Society depends on the economy - and the economy depends on the global ecosystem, whose health represents the ultimate bottom line” [6].

The financial bottom line is a substantial goal of any business, as it refers to the profit of the company. Before the public brought attention to social and ecological problems, income was the only critical issue of capitalism. Later, when the significance of the two other spheres has increased, profitability is to be associated with the welfare if the society and the planet. Thus, a new challenge of balancing between “profit, planet, and people” has arisen, as can be observed from figure 1. [6.]

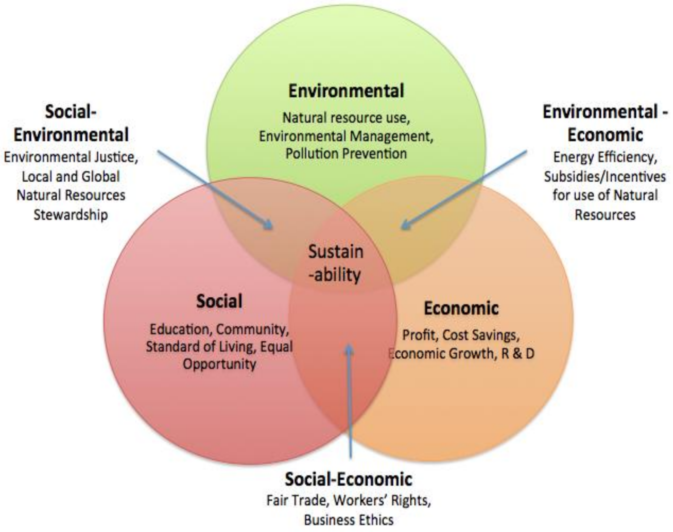

Figure 1. Sustainability challenge: Triple bottom line [8].

The social bottom line addresses the fair political and ethical treatment of people. For instance, when it comes to business, the companies are to pay attention to employees' payment and working conditions, as well as to practices in the communities within the area of operation. Moreover, the business is to have a concern for customers and other society members on a larger scale. Environmental bottom line cites the reduction of the unfavorable ecological impacts of the company, such as climate change, pollution, deforestation, and many others. Decreasing those adverse effects includes the implementation of ecological practices, such as energy saving and material recycling. [6.]

To evaluate the costs and benefits over the life of a product, Lifecycle Costing (LCC) tool is to be implemented. Lifecycle Cost Savings are prevalently attained with minimized operations and maintenance costs. For LCC estimation, utility, operation, and service costs are to be subtracted from total immediate structure costs, such as components and subsystems. The optimum balance between investments and output measured by LC can also be planned and accomplished during project design. [9.]

The environmental performance of a product can be measured with a life-cycle analysis tool, also known as life-cycle assessment (LCA). It represents research that covers the output of a business impact on the planet from raw materials extraction stage to disposal stage. [6.] Both LCC and LCA are independent indicators, so the loss of correlative data between ecological and environmental information leads to a limitation in the sustainability analysis. The solution to the problem is a further sustainability assessment tool development that allows the integration of the existing methods. [10.]

3 Sustainable Built Environment

3.1 Sustainable Construction Industry: Principles and Assessment Methods

Opposite to natural, built environment represents fundamentally everything created by humans. From a social outlook, it can be defined as a human-made space, in which people work, live, and recreate daily. On a larger extent, built environment encompasses numerous disciplines, such as real estate, law, environmental studies, architecture, engineering, and many others. Thus, cities and their buildings and infrastructure, along with urban areas, parks, roads, and pathways make up the built environment. Evidently, the key sector of the entity is construction, which is closely related to architecture and engineering. [11.] As a facility that encircles most of people most of the time, the importance and influence of built environment is of high significance for society and the environment. Nevertheless, a mass of studies gives the highest priority to the impact that the built environment has on human health, linking it to serious diseases, such as cancer, obesity, and dementia. [12.]

The value of the major elements of the built environment for society and environment is accomplished with an adequate design and maintenance processes [13]. Both processes are carried out in both building projects and infrastructure projects [14]. Infrastructure projects cover multiple interconnected services and facilities that offer comfortable living conditions for people [15]. Building projects comprise buildings and their service systems [14].

Essentially, a positive contribution to society is a substantial goal of the construction industry. However, it is one of the most massive environmental burdens with its various adverse ecological effects. For instance, construction accounts for over 30% of energy consumption, 40% of resource consumption and about 33% of carbon dioxide emissions in the world. [16.] Before the publication of the Brundtland Repor, the environmental aspect was central for construction. Later, more attention was attached to both economic and social well being. [17.]

Understanding the significance of the three SFs has led to the increase in the number of studies into sustainable construction practices throughout a project lifecycle, from initiation to closeout, represented in figure 2 [17]. Various studies acknowledge the benefits of green construction, such as cost savings, enhancement of human performance, and prestige growth of parties involved in a project [9]. Even though sustainable practices implementation commonly assigns 2.5% of the project budget increase, it is proven to pay off its value many times over the structure's lifecycle [18].

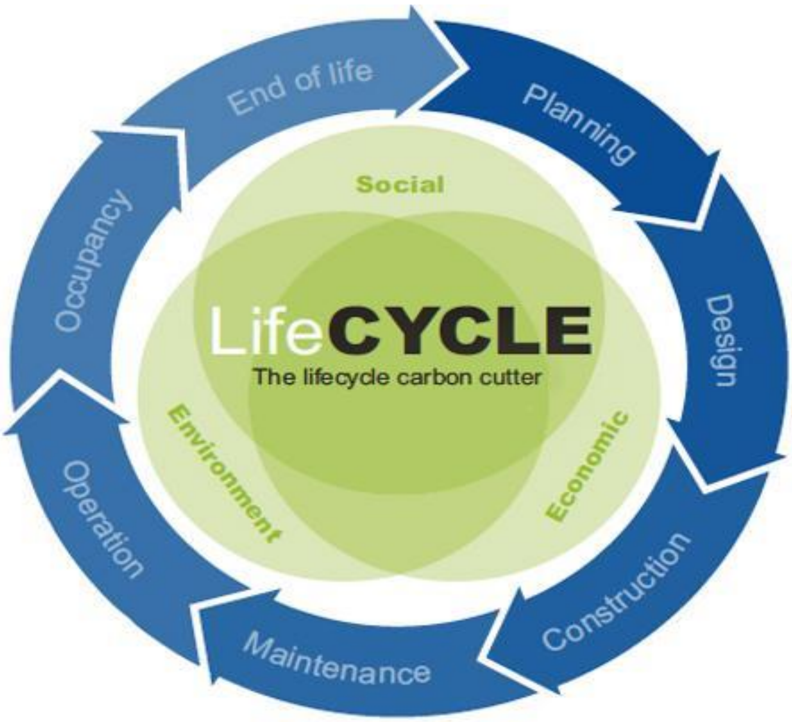

Figure 2. Sustainability within the built environment life cycle [19].

To assess the sustainability performance of a building, various evaluation tools have been developed worldwide. Currently, the most popular green building certification programs are LEED, BREEAM, SBTool, CASBEE, BCA-GM, ESGB, and Green Star. Every rating tool evaluates the sustainability level with its own set of criteria, depending on the building type and location. Except for CASBEE, each system assesses the design, construction, and operation phases of a building. CASBEE only covers the design and operation phases. Presently, LEED is considered to be the leading sustainability assessment tool. A short overview of the evaluation methods of the analysis systems can be found from table 1. [20.]

Table 1. World's mainstream building sustainability assessment systems [20].

Assessment system	**Country of origin**	**Building types**
Leadership in Energy and Environmental Design (LEED)	USA	Residential, retail, office, healthcare, data centers, other
Building Research Establishment Environmental Assessment Method (BREEAM)	UK	Residential, retail, office, healthcare, data centers, industrial, educational, other
SBTool	International	Nearly any type
Comprehensive Assessment System for Built Environment Efficiency (CASBEE)	Japan	Residential, temporary, other
Building & Construction Authority Green Mark (BCA-GM)	Singapore	Residential, non-residential
Evaluation standard for Green Building (ESGB)	China	Residential, hotel, office, commercial
Green Star	Australia, New Zealand	Industrial, educational, office, other

Whereas a large number of sustainability assessment tools are introduced for building projects, only a relatively small number of criteria are available for infrastructure. Nevertheless, a variety of sustainable infrastructure solutions are being developed nowadays. It is to be noted that a vast majority of current sustainable infrastructure studies concentrate on railway projects. Like building sustainability assessment tools, infrastructure sustainability evaluation systems use various sustainability analysis techniques and emphasize different factors. Currently, some of the trending infrastructure sustainability assessment tools are INVEST, CEEQUAL, and GreenLITES. It is worth mentioning that infrastructure analysis systems are often elaborated from building assessment systems, as in the case of CEEQUAL, the concept of which originates from BREEAM. Further infrastructure sustainability rating system data are shown in table 2. [21.]

Table 2. Infrastructure sustainability assessment systems [21].

Sustainability assessment system	**Country of origin**	**Key analysis factors**
INVEST	USA	Environment, society, economy, engineering
Civil Engineering Environmental Quality Assessment and Award Scheme(CEEQUAL)	UK	Environment, society, engineering, project administration
GreenLITES	The USA	Environment, engineering

An example of the benefits of sustainable design is the University of British Columbia Life Science Center, which was Canada's largest LEED gold-certified facility in 2005. For instance, to meet the requirements of a tight schedule, a modular construction approach was implemented. Also, wherever possible, the lighting system of a building relies on daylight. As a result of various sustainability-oriented procedures, the water use dropped to 50% compared to traditional construction, 80% of the construction waste products were efficiently recycled, and the energy use was reduced by 30% compared to the American Energy Standard for Buildings. [22.]

Bloomberg's New European Headquarters in London is acknowledged as the most sustainable office building in the world. It scored 98.5% of the points in BREEAM in 2017. Most considerable of the implemented practices are natural ventilation, water conservation system, smart air flow, combined heat and power system, and multi-purpose ceiling panels. The Bloomberg Headquarters consumes 73% less water and 35% less energy compared to a conventional office building. Thus, significant cost savings and carbon dioxide emission reductions were obtained. [23.]

In 1996, the city of Växjö in Sweden set a goal to become fossil-fuel independent by 2030. After that, a variety of sustainable actions were promoted. For instance, the city utilizes energy-efficient centralized district heating and cooling systems, while public transport runs on renewable fuels and biogas. The waste products of the local forestry industry are effectively utilized in a combined heat and power plant. Moreover, sustainability philosophy is actively promoted within the community. As a result, in 2014 Växjö accounted for only one third of the average EU city carbon dioxide emissions. Furthermore, the economic growth of the area is strong, because the gross domestic product (GDP) per capita has increased by 90% between 1993 and 2012. [24; 25.]

In 2016, Arcadis Design & Consultancy acknowledged Vancouver as the most sustainable city in North America [26]. In its Greenest City Action Plan, Vancouver defined a set of goals to be achieved by 2020: strong local economy, inclusive community, and consideration of the needs of the future generations. In recent years, the city has been promoting green transportation, recycling activities, local products, and many other alternatives. From 2006 to 2018, the city implemented new strategies, which led to a 23% landfill waste reduction, 20% ecological footprint decrease, 36% traveling distance decline per person. From 2010 onwards, a 49% increase in the green jobs market has taken place. [27.] Moreover, in 2018, Vancouver, with its 2.7% GDP growth, was the city with the fastest growing economy in Canada [28]. According to a wellbeing consulting company, Mercer, Vancouver tops the list of cities with highest living standards among cities of North America in 2018 [29].

In 1994, the Conseil International du Bâtiment (International Council for Building), defined sustainable construction as "...creating and operating a healthy built environment based on resource efficiency and ecological design" [30]. Therefore, based on TBL concept, six key principles of sustainable construction can be constituted [17]:

- Healthy, safe, and productive built environment for people in harmony with nature
- Fulfilling today's needs while securing the necessities of the future generations
- Evaluation of social and environmental benefits and costs of a project
- Minimization of environmental losses
- Social unity procuring by improving buildings and services quality

- Project enhancement by information seeking.

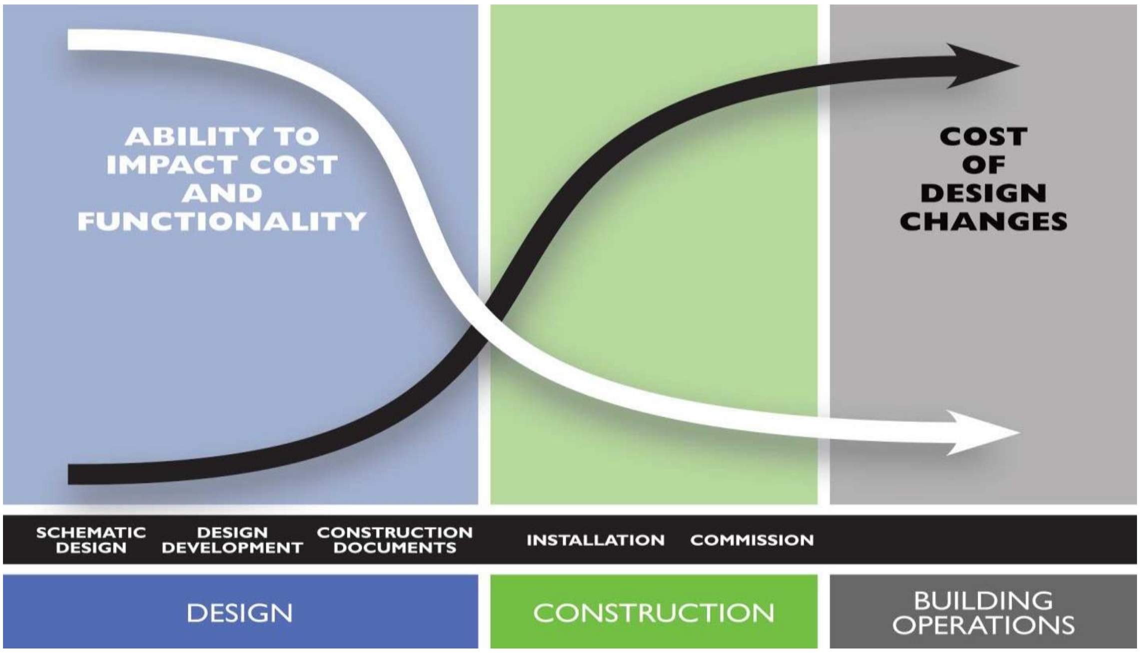

Figure 3. Costs of design changes within project phases [31].

As can be observed from figure 3, the project design phase is the optimal period to achieve the sustainability of the construction. At the later stages, modifications demand higher costs and provide fewer decision options. Therefore, the implementation of sustainable initiatives is most favorable at the project inception. [32.]

3.2 Sustainable Infrastructure Review

Infrastructure is a complex network of interrelated basic facilities and services that provide an adequate environment for human living. An urban infrastructure system includes a variety of facilities, utilities, and services, from diminutive items to major entities, such as a railway, water supply network, sewage system, and an electricity grid. As an inherent auxiliary sector of the region, infrastructure is acknowledged to be a substantial factor for economic and social development of an area. [15.]

For sustainable planning, it is important to take extensive social and environmental dimensions of infrastructure into consideration. When this is done, global problems, such as social inequality or climate change, can be solved efficiently. [33.] Due to its complexity, high costs, and time expenditure, infrastructure project development addresses an extensive number of objectives. Therefore, introducing sustainability to the outline is a highly sophisticated task. [21.]

Altogether, the infrastructure system's sustainability is measured by its impact on the economy, society, and environment [21]. In other words, the primary purpose for sustainable infrastructure management is to achieve the highest performance level of a system with a minimum of possible environmental and economic costs [10]. The International Institute for Sustainable Development (IISD) lists sustainable infrastructure principles along these lines [34]:

- Concern for natural ecosystems
- Lower environmental and carbon footprint
- Optimization of infrastructure potential of natural ecosystems
- Respect for human rights and labor wellbeing
- Innovation pursuit
- Investments in related research and education
- Employment rate growth along with green jobs emphasis
- Financial feasibility
- Involvement of enthusiastic local companies and investors
- External investments growth
- Value for money guarantee.

When the high need for sustainable infrastructure had been realized, a large number of countries brought investments into corresponding research and project development. New construction approaches, methods, and materials are implemented to achieve higher environmental performance and quality for people. To reduce greenhouse gas emissions, modern environment-friendly means of transport are introduced. Furthermore, depending on the area, present social and economic demands are also considered along with environmental needs. [35.] Nevertheless, the process of a global shift from traditional to sustainable infrastructure is at its initiation phase due to the extent of the problem, and high investments in both time and money [21].

3.3 Sustainable Bridge Considerations

According to the Cambridge Dictionary, a bridge is a structure that is built over a river, road, or railway to allow people and vehicles to cross from one side to the other [36]. As integral elements of transport infrastructure, bridges significantly affect the social, economic, and environmental spheres of an area [18.]. For instance, India is planning to invest $1.7 trillion in infrastructure projects to promote economic growth [37]. As high-quality infrastructure segments, bridges are capable of bringing a healthier and more productive environment for people. However, bridge construction can be a risk for the natural resources and aboriginal communities if an area. Therefore, the highest possible sustainability performance of bridges is of essential importance. [18.]

Once conventional, green, and sustainable construction, respectively, is defined, it becomes clear that these terms are connected. Most often, the purpose of conventional construction is to make a profit and to provide quality for people. Green construction, above all, emphasizes environmental aspects. Sustainable construction, in its turn, covers the criteria of both conventional and green building principles: profit, and quality for people, and the environment. Thus, it is evident that sustainable construction covers the criteria of both traditional and green building, while providing an optimal balance between them. Depending on the structure, even more measures can be added to this construction vision. [38.]

It is possible to distinguish six main structural form types of bridges (see figure 4): beam/frame bridges, arch bridges, cantilever bridges, suspension bridges, cable/stayed bridges, truss bridges, and suspension bridges. Bridge construction involves a variety of materials, yet nowadays the most important ones are reinforced concrete, prestressed concrete, and steel. According to their purpose, bridges can be categorized as highway, railroad, road, or pedestrian bridges. The design is to resist dead, live, wind and earthquake loads, as well as impact loads. The moving vehicle impact requires extensive consideration due to its complexity. A primary claim for the safety provided by the structural design of a bridge is that load-bearing capacity should always exceed the demand, which is permanently growing. [37.]

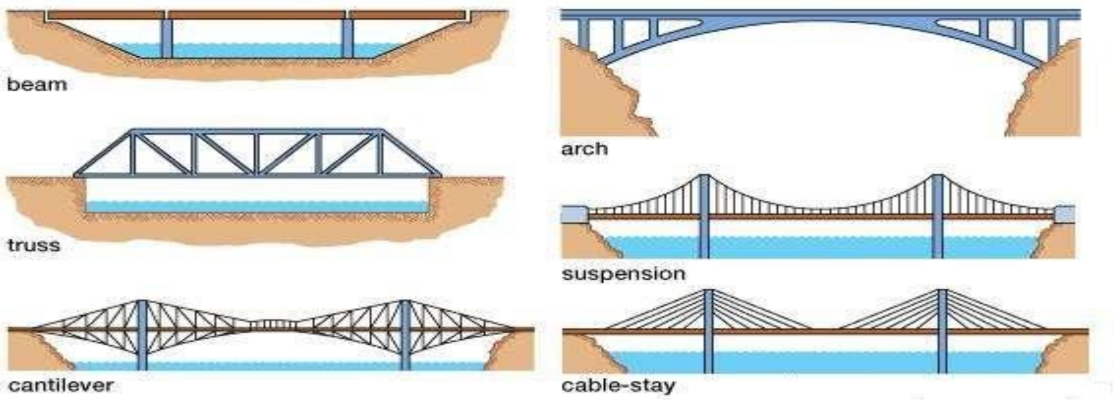

Figure 4. Main structural form types of the bridges [39].

Currently, a multitude of steel bridges around the world are reaching their service life limits [40]. Concrete bridges are subjected to a lack of durability, characterized by early deterioration and depletion [41]. As the traffic loads are increasing continuously, a vital safety question arises. For example, on August 14th, 2018, the Genoa bridge collapse led to lethal consequences. Insufficient design and maintenance, further inattention to these, and higher traffic loads were acknowledged as reasons for the structural failure. [42.] Hence, the present need for sustainable bridge design and maintenance is crucial [37].

A sustainable bridge can be defined as a structure that is built fast with optimum resource exploitation for long-term efficient performance, along with minimum surrounding disruption and with no wasted materials [37]. Similarly to other construction projects, the bridge's pursuance of sustainability is measured with three indicators: social impact, environmental protection, and economic development influence [40]. Traditionally, bridge design mainly takes into account construction phase of a structure, and cost minimization within that period. For sustainable development promotion, a conventional process is to be expanded to the entire bridge life cycle. As can be seen from figure 5, the bridge life cycle design generally takes into account the service requirement, financial costs, culture, and ecology. [43.]

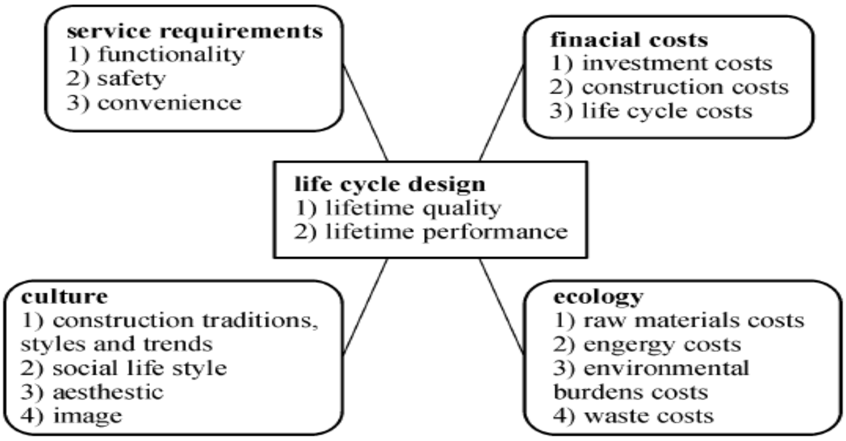

Figure 5. Bridge life cycle design [43].

The environmental effect of a bridge can be, first of all, analyzed on the basis of processing and later utilization of the construction materials and corresponding activities involved in the process. Another important ecological factor is the area disturbance during the construction and utilization phases. Certainly, sustainable construction principles underline minimal disturbance for the biota. The economic performance of a bridge can be evaluated on the basis of the economic integration of an area while ensuring travel time and costs minimization for the consumers. Similar to the purpose of every infrastructure object, the first social objective of a bridge is to improve the users' quality of life. Properly planned and designed, a bridge can provide high-level equity and exclusion in the region. Nevertheless, inadequate design and maintenance can lead to negative health effects or even deadly consequences. [44.]

Presently, an insufficient amount of formal criteria and recommendations are available for a sustainable bridge, because its framework is still under development. Nevertheless, some infrastructure sustainability evaluation systems, such as GreenLITES, have been employed in bridge projects. Furthermore, there are two other sustainability evaluation systems meant for bridges: Snelling and Hunt. In an attempt to create an efficient bridge sustainability assessment method, M. Yadollahi, a senior lecturer at the Malaysia University of Technology, and his colleagues have developed a multi-criteria analysis for the Penang Second Bridge (P2B) case study. The assessment is based on four authoritative transport infrastructure rating systems: Snelling, Hunt, GreenLITES, and Greenroads. Moreover, Yadollahi was cooperated actively with the committee of Malaysian bridge professionals during the study. Multi-criteria decision-making (MCDM) was effectively implemented to compare and, subsequently, to justifiably distinguish the most important sustainability factors (SFs) in the three main aspects of sustainability: the ecological, economic, and social ones. [44.]

As a result of Yadollahi's research, 13 SFs for bridge were listed. In the Penang study, a summary of the sustainability considerations was provided for each SF, as can be seen in appendix 1. Though the SFs stated in the table can be used to rate any bridge, the sustainability considerations are project-specific and are not always possible to directly apply to all structures. Nevertheless, it should be noted that the sustainability considerations of the analysis system for SFs in Yadollahi's study are discussed in relation to the Penang Second Bridge (P2B). [44.]

4 Sustainable BIM Applications in Bridge Design

4.1 BIM: Industry Foundation Classes and Sustainable Development

Building Information Modeling (BIM) is "the use of virtual building information models to develop building design solutions, to design documentation, and to analyze construction processes". However, BIM is a comprehensive tool, and its definition is to be extended to the operational phases of the built assets, as well as to the entire civil construction field. BIM presents itself as an extension of computer-aided design (CAD), which links the 3D built property model to a relative asset database. Thus, BIM provides an elaborated platform for communication between construction industry professionals, such as engineers, architects, contractors, and facility managers. BIM has a potential to solve the problem of miscommunication that has prevailed in the construction spher. [45.] Another benefit that BIM brings to the project is the possibility to re-use information that enables a higher level of clarity, consistency, accuracy, and authorship responsibility. Thus, BIM is a tool that is highly beneficial for enhancing the efficiency and sustainability over the whole life cycle of a construction project. [46.] Altogether, 13 main spheres for the employment of BIM can be highlighted from academic papers [47]. Appendix 2 presents the purposes and related building project examples of BIM, along with a description of particular tools and methods. Appendix 3 introduces the uses of BIM in infrastructure projects.

On the basis of the review in appendix 2 and appendix 3, it could be concluded that BIM allows optimum design decisions by enabling better project insight by professionals. That is achieved with a possibility to evaluate various project performance alternatives before the construction phase. [48.] At an early stage, BIM grants a possibility to assess the project's structural behavior along with its environmental performance. Furthermore, BIM makes it possible to detect clashes before the construction phase and, subsequently, significantly reduces work costs. BIM-based scheduling and logistics monitoring and optimization also lower the cost and time demands of the works. For construction workers, mobile applications allow access to integral real-time design information, thus providing a clear understanding of the action scheme. During the operation phase, BIM-based high precision structure systems monitoring and facility management systems can be implemented for constant facility service quality improvement. In any case, there is a large number of BIM employment aspects in the construction industry, and for each of them, the respective existing tool can be selected. For decommissioning, BIM can provide all the sufficient information on the structure's lifecycle and construction materials, thereby increasing demolition safety level and decreasing the time required for the process completion. [47.]

To sum up the information mentioned above, BIM integration allows most favorable decisions possible due to the quality increment, high-speed and design information accessibility. Therefore, BIM is an enhanced tool to take the triple bottom line challenge within the AEC industry. In other words, BIM can be beneficial for the environment, society, and economy. For the environment, BIM can decrease the material and energy needs of a project significantly. For society, BIM enhances safety and collaboration practices, while providing a new range of opportunities, such as innovative BIM consultancy jobs. For the economy, BIM allows highly efficient financial decision making with savings of time, energy, and materials. [47.]

At the moment, 72% of construction companies in the USA are accredited for BIM implementation for major cost-saving purposes. The government, various private organizations, and universities support the idea of higher adoption of BIM standards. BIM was also rapidly adopted in the UK where it reached 54% in 2016, compared to 48% in 2015. Therefore, the UK is considered one of the world's leaders in BIM adoption. Furthermore, Scandinavian countries are acknowledged to be among the earliest BIM adopters. For instance, BIM utilization rate in Sweden is so high that even without clear government guidelines the best practices have emerged. In Germany, although 90% of the project owners require BIM employment, its adoption rate is still relatively low. In 2015, the government of Germany initiated a platform for developing a national BIM strategy, yet some experts apprehend that the federal system of Germany might substantially slow down the speed of the initiation. The Singapore government has established a centralized archive for building codes and regulations. Since 2010, BIM fund covers some costs, such as training, consultancy, hardware, and collaboration software. China, with its 15% BIM employment in the construction industry, presents a low BIM utilization level. Furthermore, BIM engagement in projects is not mandatory. Along with the Scandinavian countries, South Korea presents itself as an early BIM adopter, as its government has been systematically encouraging BIM employment. [49.] However, BIM adoption worldwide is associated with quite a few challenges, such as added designer work or complexity of BIM. Nevertheless, a large number of experts have forecasted that BIM uptake in the AEC industry will be slow, but inevitable. [46.]

When it comes to BIM software in particular, six main categories of tools can be distinguished: architecture tools, sustainability tools, structures tools, mechanical tools, electrical tools, and plumbing (MEP) tools, construction simulation tools, and facility management tools. Table 3 provides an overview of software categories along with examples. It is worth mentioning that Autodesk Revit presents one of the world's leading BIM tools due to the inclusion of architectural, MEP, structural, and construction functions. According to the NBS National BIM Report, Autodesk Revit accounts for a total of 41% of BIM implementation. In comparison, the second software prevailing in the UK, Graphisoft ArchiCAD, accounts for only 13%. Due to its multidisciplinarity, Revit provides an environment for a collaborative design process. Also, depending on the project demands, various Revit add-ons, plugins, and extensions are available on the market. [50.]

Table 3. BIM software categories and examples [50].

Category	Software examples
Architecture	Autodesk Revit Architecture, Graphisoft Archicad, Bentley Architecture, RhinoBIM(BETA)
Sustainability	Autodesk Green Building Studio, Graphisoft EcoDesigner, Autodesk Ecotect Analysis
Structures	Autodesk Revit Structures, Tekla Structures, Autodesk Robot Structural Analysis, Bentley Structural Modeler
Mechanical, electrical, and plumbing design	Autodesk Revit MEP, CADMEP
Construction simulation and analysis	Solibri Model Checker, Autodesk Navisworks, Tekla BIMsight
Facility Management	Bentley Facilities, Onuma System, EcoDomus

To enhance effective information exchange between the parties involved in a project, so-called 'Open BIM standards' have been defined. One definition of the Open BIM is "...a universal approach to collaborate design, realization, and operation of buildings based on open standards and workflows" [50]. In other words, interoperability of data transfer among applications is to be achieved with various information exchange formats. A standard is a formal and central definition of the process and information conventions assigned in a document. Standards can be categorized with respect to the format of the data carrier, language agreements, and processes, e.g., who and when provides specific information. For any possible future needs, BIM standards can keep information usable in the long-term. Thus, BIM makes it possible to avoid the data recreation or re-input of data. Therefore, there is an opportunity to save costs and time within the project. On the other hand, software non-interoperability commonly leads to a 3.1% of the total budget increase in the US. Table 4 describes several standards in brief and provides names of organizations that manage each format. [51; 52.]

Table 4. Open BIM Standards [52].

Standard	Organization in charge	Description
Industry Foundation Classes (IFC)	buildingSMART	Internationally standardized data model exchange between professionals and software
CB-NL	Bouw Informatie Raad (BIR)	Digital description of reusable concepts linked to physical objects
CityGML	OGC/Geonovum	An information model for the description of urban objects in 3D
Information Model Geometry (IMGeo)	Geonovum	3D geo-information exchange

In Europe and, specifically, in Scandinavia, a multitude of countries have made the use of the Industry Foundation Classes (IFC) format mandatory [53]. For example, Common BIM Requirements 2012 by buildingSMART Finland demand IFC format implementation along with the software's native format for all public projects [54]. In short, IFC is a neutral data format used for information description and exchange across multiple software and parties involved in the project. It should be noted that the format has been registered by the International Standardization Organization (ISO) as ISO 16739 "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries". In 2000, IFC 1.0 was addressed. In 2013, the latest IFC4 version was released and upgraded to IFC Add2 in 2016. Currently, IFC is endorsed within 150 BIM software applications around the world. [55; 56.]

As observed in figure 6, the IFC data model structure consists of four layers: domain, interoperability, core, and resource. The pattern is strictly hierarchical, which means that top-down referencing can merely take place. Resource layer information is to be irrespective and not to refer to classes above it. Nevertheless, other layers may relate to the resource layer information, as well as to data on all the layers below them. Furthermore, referencing within the layer is only possible for the resource layer. The resource layer carries so-called resource schema that comprises basic definitions dedicated to object specification of above layers. The core layer encompasses a kernel and extension modules. The kernel designates the structure of the model and its decomposition while maintaining basic data relative to objects, relationships, attributes, type definitions, and roles. On a par with the Kernel, the Product extension module, IfcProduct, is an abstract representation of every object that refers to geometry or space. Accordingly, it consists of multiple physical building elements, such as IfcWall, IfcDoor, IfcBeam, IfcStair, and IfcWindow. Moreover, the IfcProductExtension covers elements related to spatial dimensions: IfcSpace, IfcBuilding, IfcSpace, and IfcSite. Furthermore, it includes immaterial elements associated with the spatial or geometric scopes: IfcAnnotation and IfcGrid. [51.]

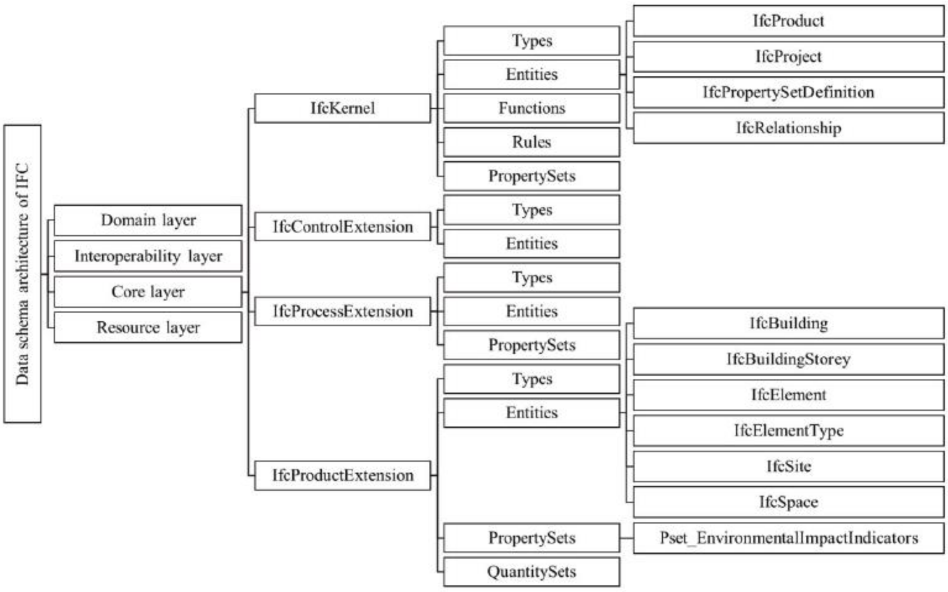

Figure 6. IFC data model structure [51].

Module extensions specialize on classes which are designated in the kernel. At the same time, the interoperability layer ensures the domain models interface, comprising schemas that include entity definitions distinct to a product, resource or process specialization engaged in several disciplines. The domain layer embodies schemas comprising entity definitions that are products specializations, processes, or specific resources related to a particular discipline. [51.] Another IFC data schema architecture along with components of the layers can be observed from figure 7.

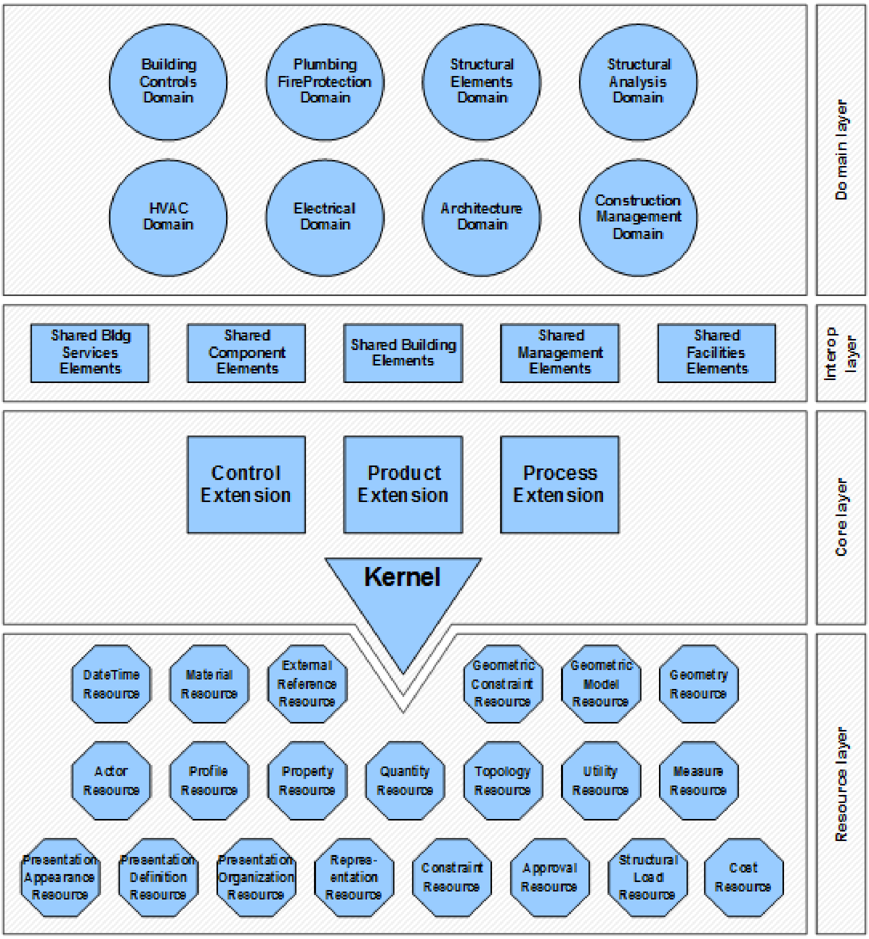

Figure 7. IFC data schema architecture with conceptual layers [57].

At the moment, an IFC Bridge standard, or IFC Bridge in short, is under the process of development. In 2018, a draft was already released. By now, IFC Bridge encompasses the primary structural parts of bridges, such as the deck, pier, and footing. Furthermore, main bridge types (see figure 4) are also paid attention to. In addition to that, a sectioned spine is to be taken into account. Moreover, transportation object data are to be anticipated for design and construction purposes. Essentially, a standard customized for bridges will presumably further integrate digitalization principles into the design, execution, and operation of a bridge project. [58.]

4.2 Bridge Sustainability Assessment System

Previously, the major sustainable bridge factors (SFs) were defined by Yadollahi [44]. Based on that information, a preliminary report composition and analysis data can be designated. In other words, Yadollahi's SFs can be used as generalized criteria. Nevertheless, the summary of the considerations in the SFs in Yadollahi's work is project-specific and, thus, cannot be used at its full extent for the development of an analysis algorithm that could be employed for the assessment of various projects. Therefore, a need for more specific criteria for bridge SFs has arisen. As can be observed from table 5, each bridge SF can be ranked from 0 to 10, where 10 is a prime performance indicator. The innovation sustainability factor represents unstructured data that cannot be described in any of the other categories. Therefore, it was not included in the template of the report (see table 5), because a computer program is not able to assess uncategorized data without user's help. Though a water quality SF is a considerable indicator for nearly every construction project, it can be more distinctly described within other SFs as a parameter. Therefore, it was excluded from generic bridge assessment. In this thesis, an attempt was made to develop Yadollahi's bridge sustainability assessment system by supplementing the SFs with parameters which are valid for most of the bridges.

Table 5. Final bridge sustainability analysis report template [44].

Sustainability factor	**Rating**
Materials and resources	0..10
Project delivery process	0..10
Construction activity	0..10
Maintenance and access	0..10
Environment and atmosphere	0..10
Energy efficiency	0..10
Traffic efficiency & alternative transportation	0..10
Sustainable site	0..10
Equity and social issues	0..10
Pavement technologies	0..10
Sum	0..100

As can be observed from the bridge sustainability assessment system suggested by Yadollahi (see appendix 1), each SF covers multiple measures. In this final year project, a research was carried out to define the most common parameters for Yadollahi's bridge sustainability analysis system. While Yadollahi's work concentrates on a particular bridge, this paper attempts to compile a general-purpose evaluation framework of any bridge. Thus, five measures in each factor were considered enough for a prototype of an analysis tool for bridge sustainability drafted in this study. Nevertheless, a broader criterion is to be considered in order to obtain valid results for an actual project evaluation. In addition, as can be observed from table 5, all SFs are of equal weight. That is because, according to Yadollahi, the weights are to be determined on the basis of the regional requirements. In the Penang Second Bridge study, Yadollahi et al. utilized the analytic hierarchy process (AHP) to determine the values of the SF for the particular area on the basis of local legislation. [44.]

In this paper, an attempt is made to create a framework for most bridge types located around the world. Therefore, the weights of SFs are kept at the same level with a strong recommendation to reconsider them when the project location is known. Within the SFs, values of the parameters should be conserved, because an effort was made in this study to distinguish parameters with an equal weight. Furthermore, some conditions of the parameters in the SFs are of a fairly numerical requirement, such as recycled content percentage. For example, recycled material parameter in materials and resources SF is awarded 8 points when the recycled content of a material is 80%. Other parameter conditions do not correspond to numerical value, as they, for instance, demand particular system installation with specific requirements. When the value is not numerical, the condition satisfaction output can have a “True” or “False” value that is to be confirmed by a human, a professional in the field. In other words, a person is to confirm that the system answers the requirements of the condition. For instance, area disturbance minimization parameter in construction activity SF is awarded 1 point per each disturbance minimization activity, altogether 10 points.

A further developed version of the bridge sustainability assessment system is to be more automated. Nevertheless, such system will presumably have a larger number of parameters and dozens of sub-parameters. Some conditions of parameters in the SFs mostly refer to action strategies and legislation, as those SFs are highly extensive, and no narrow parameter condition can reliably represent the reality. Thus, as mentioned above, quality assurance within these parameters is still to be carried out by the professional.

Appendix 4 presents more detailed sustainability measurements which are relevant for a vast majority of bridge projects. As bridges belong to the AEC sector, criteria is taken into account on the basis of the industry experts' sustainability standpoint, essentially drawn from the triple bottom line concept.

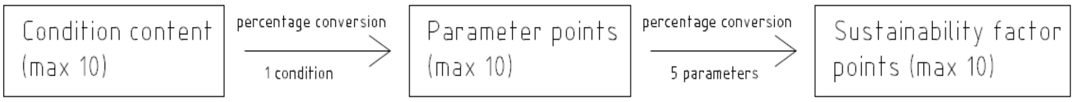

Figure 8. Point conversion concept within bridge analysis system hierarchy.

Each parameter is awarded from 0 to 10 points where 10 points are assigned upon the achievement of the prime performance within one the parameter condition. Conditions within parameters are selected in an attempt to represent the most reliable context indicators. Nevertheless, multiple conditions are recommended within the parameter for higher precision outcomes. Thus, each factor can be assigned a maximum of 50 points, which correspond to a maximum of 10 points for each SF in the final template of the report (see table 5 and figure 8). Thus, one parameter accounts for 20% of a SF. Also, a multitude of conditions for the parameters are numerical or lead to a numerical format, so that the points are to be calculated. If the parameter situation is in between, such as 94% outcome for percentage condition, the value is to be lowered to 90% during the conversion. As a result, points for the parameters and SFs are always integers. Moreover, some parameter conditions are only satisfied as either 0 or 10 points, while other parameter values can vary from 0 to 10. Variation is usually due to the level of performance, while 0 or 10, respectively, correspond to "No" or "Yes". Such "Yes" or "No" occurs when, for instance, some equipment installation is required, and its further performance is complex to evaluate. Thus, only equipment presence is considered. As previously mentioned, the quality of such equipment is to be verified by an appropriate professional. This research found out that parameters and conditions of the SFs are often closely interrelated. Depending on the perspective, some parameters and conditions may be referred to more than one SF. However, an effort is made to place parameters and conditions to the most relevant SF. Below, each of the ten sustainability factors in table 5 are discussed in more detail.

4.2.1 Sustainability Factor Materials and Resources

When it comes to the sustainability performance of construction resources and materials, an extensive definition was given by Glavic and Lukman [59]: “ Sustainable material is a product made using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for consumers and which are socially and creatively rewarding for all stakeholders for the short and long-term future”.

It is evident that characteristics of some sustainable materials given by the definition can be quantified when others present themselves as rather subjective measures. By analyzing the five main properties can be highlighted as quantifiable features of the materials: recyclability content, low-emitting contaminants, rapid renewable periods, low energy consumption, and durability. However, most social performance of materials is non-quantifiable and, thereby, can not be included in the assessment system. Accordingly, the most important parameters of construction materials refer to the environmental sphere of sustainability. [59.]

Clearly, the highest possible and most desirable recyclability content of the material is 100% with an emissivity level at the lowest potential degree, which corresponds to 0%. Thus, Contaminants emissivity parameter is to be assigned 10 points if the material is non-emitting. With each 10% increase in emissivity, the parameter is to lose 1 point. For recycled compound, 100% content of the recycled aggregate in the material contributes to 10 points within recycled content, while each 10% drop deducts 1 point. Most rapidly renewable construction materials are plant-based matters, which can be supplemented within 10 years. [60.] On this basis, if the material is renewable in maximum 10 year period, renewable period parameter it is to be assigned 10 points. With each decade added to the renewal time, one point is to be subtracted from the rating.

When it comes to life cycle evaluation of the construction material energy and resource performance in the building sector, primary attention is usually paid to the operation phase. The situation is the opposite for bridges, that is to say, bridge material extraction, production, delivery, and disposal phases play the most important role in the sustainability assessment. Therefore, embodied energy, or total energy required for production can be sufficient for general representation of the bridge construction materials energy consumption. Nevertheless, as this data represents only one phase of the entire product lifecycle, it does not present the final energy value within life cycle of a material. Also, sustainable material approach promotes recycling, which is often less energy demanding than production. Therefore, energy consumption level of material disposal is considered to be lower than that of production. [61.] According to Sabnis, the embodied energies of the most common construction materials vary from 0.1MJ/kg (aggregate) to 155MJ/kg (aluminum) on average. Thus, the material can be awarded 10 points for the energy consumption parameter if its embodied energy equals to 0.1MJ/kg or less, and 0 points when the value equals to or exceeds 155MJ/kg. [62.] Energy values in between are to be interpolated with the deviation towards a smaller amount of points.

Durability is another important consideration in material selection. There are 10 types of durability: dust resistance, fatigue resistance, ageing resistance, radiation hardening, fire resistance, thermal resistance, rust-proofing, rot-proofing, waterproofing, and toughness. Acknowledgement of each type of durability by a professional corresponds to 1 point. [63.] As road and railway traffic load values keep increasing, material savings are to be considered in respect to the entire life cycle of a structure [42]. Thus, anticipatory bridge demolishment due to insufficient capacity can be avoided. Presumable maintenance and repair activities throughout service life of a structure are described in Maintenance and Access SF chapter. Average environmental performance of all the materials utilized in a project is to be evaluated within Materials and Resources SF.

4.2.2 Sustainability Factor Project Delivery Process

A bridge project delivery, like any construction project delivery, is a comprehensive process that encompasses planning, design, construction and other activities involved in the execution and completion of an AEC object. The operation commonly involves three parties: the owner, designer, and builder. Today, there are four widely used project delivery methods (PDMs): Construction Management at Risk (CMR), Design-Bid-Build (DBB), Design-Build (DB), and Multi-Prime (MP). Project requirements have a great impact on delivery method selection as the method highly affects the project workflow and outcomes. The choice of PDM is one of the most important choices the owner has to make because it has a great influence on other factors, such as project quality, cost, efficiency, and, time consumption, in particular. [64; 65.]

As advantages and disadvantages of each PDM have been researched widely, the choice of most and least sustainable one is a complex problem that is best solved according to the project type, requirements, and a variety of other factors. Thus, efficiency, quality, and costs can be seen as relevant indicators for the choice of the project delivery process since then can be interpreted and compared.

Various studies state that the quality, cost, and efficiency of a construction project depend highly on the communication between the parties involved, as well as the schedules and worker's expertise. [67; 68.] On the other hand, 85% of the construction projects in the world exceed the budget plan and 92% are not carried out in time. Moreover, 63% of the AEC projects do not meet quality requirements. [66.] Most commonly suggested solutions to the problem are a powerful communication platform, effective timetable, and employee's professional skills development. Meanwhile, operation transparency of companies and the fair treatment of workers are not to be compromised. [67; 68.]

BIM has been shown to be a very powerful communication platform for the AEC industry that brings together the customer, designer, contractor, and other parties. Moreover, BIM allows a noticeably higher quality and efficiency level of the design process compared to traditional CAD practices. Thus, BIM adoption level can represent one of the major parameters within the project delivery process. [67.] One demonstrative indicator of the BIM levels defined by BIM Industry Working Group (BIWG) in 2011 (see table 6). [69.]

Table 6. BIM levels by BIWG [69].

Level of BIM	Description
Level 0	Unmanaged CAD probably 2D, with paper (or electronic paper) as the most likely exchange mechanism
Level 1	Managed CAD in 2D or 3D format using BS1192:2007 with a collaboration tool providing a common data environment, possibly some standard data structures and formats
Level 2	Managed 3D environment held in separate discipline 'BIM' tools with attached data. Commercial data managed by an Enterprise Resource Planning application (ERP). Integration on the basis of proprietary interfaces or bespoke middleware could be regarded as 'pBIM' (proprietary). The approach may utilise 4D programme data and 5D cost elements as well as feed operational systems
Level 3	Fully open process and data integration enabled by web services compliant with emerging IFC/IFD standards, managed by a collaborative model server. Could be regarded as iBIM or integrated BIM potentially employing concurrent engineering processes

According to table 6, development degree of BIM can be determined on 3 levels where level 0 corresponds to CAD design only. Level 0 can be awarded 1 point in the BIM adoption parameter, while every consequent level achievement measures up to an extra 3 points. If BIM is not implemented in the project workflow, the parameter is to be 0 points. The BS1192:2007 mentioned in level 1 description in the table is a British code for collaborative production of AEC information. Therefore, a standard corresponding to BS1192 can be implemented for projects based outside of the UK.

Another important factor for successful project delivery is an efficient timetable. Many companies and researches suggest a large variety of methods to keep up with the schedule, while main helpfulness indicator of a timetable is the amount of a holdup time. A qualified project manager is to make sure that the project timetable is composed so that work timing is realistic, and the possible negotiation periods and errors are taken into consideration. [70.] Chehrehpak and Alizadeh classify four levels of delays: 1 - no delays; 2 - under one month; 3 - one to three months; 4 - over three months [71]. For the bridge assessment system outlined in this thesis the first delay level corresponds to 10 points, and every following level drops the value by 2 points. If the project is delayed for longer than 4 months, the original timeline parameter is to be awarded 0 points.

When it comes to the expertise of the employees engaged in the project, Chehrehpak and Alizadeh emphasize several critical success factors. Two of them are the education and experience level of personnel. The authors list the expertise levels of the project manager, workshop staff, technically responsible personnel, and executives of the organization. Education is divided to three levels with a stress on relevant university degrees: Bachelor of Science, Master of Science, and Postgraduate Doctoral Degree. [71.]

Relevant work experience is divided in three time intervals: 5 years or less, 5 to 15 years, over 15 years. Chehrehpak has carried out a success factors questionnaire among 62 project management experts. In terms of experience, it showed that project manager's and designers' expertise was highly valued. [71.] Based on this, the bridge assessment outline assigns 2 points for a Bachelor of Science or lower degree and each of the higher degrees corresponds to 4 points extra. A similar system is applied to relevant experience: less than 5 years in the industry are worth 2 points, 5 to 15 years correspond to 4 points, and over 15 years allows for another 4 points. It is enough to evaluate the experience duration and education of the design group to get a suggestive result. Experience and education level points are summarized. The skills and education level parameter of the bridge assessment system is assigned a maximum of 10 points, even if the total sum of experience and training exceeds this value.

Chehrehpak and Alizadeh emphasize the importance of transparency of the activities in a project [71]. Currently, transparency plays an important role in the USA, European Union, and some developing countries. A transparent organization provides all the relevant information about its activities to its partners. The main goal of clear and reliable information exchange between the parties is to build trust and to improve the quality of the market operations by effective decision-making. Transparency can be defined in relation to the the previous activities of a company or according to current company performance. [72.] The assessment of the transparency performance of a particular project needs to evaluate the information flow related to the project. There are seven main types of construction information: construction techniques, time, resources, cost, quality, safety, and supporting information, also referred as other information. Furthermore, each parameter encompasses several aspects. According to Guo, resources, construction techniques, and cost information weight significantly high. [73.] If the three major availability of information categories corresponds to 2 points and the others account for 1 each, then the transparency parameter of the bridge assessment system has a total of 10 points. Availability of information should be analyzed on the basis of the parties' satisfaction with the provided information.

Fair employee treatment concept is based on the fact that all people have basic human rights regardless of their sex, age, race, or political and religious status. Fair treatment of workers includes respect of an employee's right for privacy, submitting reasonable feedback on the work done, avoidance of any type of discrimination, adequate working conditions, as well as fair rewards for performance. [74.] An employer's reputation in public, and in legal sphere, depends highly on employee treatment. Moreover, an unfair attitude to employees is shown to the reduce productivity at the workplace significantly. [75.] A questionnaire among workers is one of the most effective ways to assess the level of the performance of an organization in terms of regard to employees. [76.] Thus, a direct proportion can be introduced between the satisfied employee percentage and a maximum of 10 points for fair employee treatment parameter in the bridge sustainability assessment system outlined in this thesis.

4.2.3 Sustainability Factor Construction Activity

Sustainable construction activity refers to site-related operations in the first place. Construction activities frequently contribute to a large scale air and ground pollution, leading to thousands of lethal consequences around the world. Thus, a need to minimize negative environmental effects arises. To achieve sustainable site operations during construction, several studies recommend to pay primary attention to construction waste reduction and disposal, transportation need reduction, area disturbance minimization, pollution prevention, and supply chain rationality. [77; 78.]

Construction waste is a quantity of excess building materials which were not utilized during construction and, therefore, should be disposed of. Construction waste highlights losses of natural resources used in production. Furthermore, the waste contains various hazardous contaminants that are dangerous to both humans and the environment. In addition, construction waste demands large landfill areas, thereby reducing land resources. Globally, from 57% to 85% of the construction waste is offloaded in open dumps and landfills. The strategy required to solve the waste management problem encompasses involved awareness of the involved parties, monitoring of real-time situation, analysis, and action. [79.] LEED v4 emphasizes that construction waste disposal by landfill or incineration can be primarily avoided by recycling and reusing [80]. Thereby, recycling each 10% of total waste reduction can account for 1 point within waste management parameter.

Similarly to the AEC sector, the transportation sector also accounts for a large amount of emissions. The reduction of construction transportation emissions is commonly associated with proper transportation planning, environmental performance of the vehicle, and travel distance from the point of supplies to the construction site. Various sources recommend paying attention to travel distance considerations above all, because it can be quantitatively assessed. All parties are encouraged to minimize travel distances and to carry out local purchases, to buy local materials from local suppliers. [77; 78.] According to Simmie, local supplies are the ones located within 50 km from the place of consumption [81]. Therefore, if the supplier's place of raw material extraction and later production is located not further than 50 km from the construction site, transportation parameter score corresponds to the maximum 10 points. With each extra 50 km added to the supply distance, awarded points of the parameter are to drop by 1 point in bridge analysis system.

Construction-related activities frequently cause various disturbances for the inhabitants of an area. Zone disturbance mitigation is generally managed by local regulations and on the initiative of affected parties. Many of governments and organizations around the world have developed complex activities plans for disturbance mitigation. Nevertheless, the directives and their implementation are to be further improved. Furthermore, in dozens of countries, the guidelines on site disturbance mitigation may be neglected. Disturbances caused by the construction area vary greatly. Therefore, the thesis notes the ten most common types of agitation. [82-84.] The parameter is rewarded with points if efficient disturbance minimization plans by either government and other appropriate organizations are implemented [85]. Consideration of the impact of each of the following construction activities is awarded with 1 point in the area disturbance minimization parameter in bridge analysis system:

- Air pollution
- Noise pollution
- Vibration
- Dust
- Cultural heritage
- Groundwater and surface water perturbation
- Soil disturbance
- Workers’ health and safety
- Flora and fauna depletion
- Landscape and visual impacts.

Construction activities may also cause pollution with hazardous components, such as chemicals, fuel oils, concrete leachate, and many others. Commonly, accidental toxic compound subsequently turns to be a ground for land resources diminution and inhabitants’ health issues. General mitigation measures cover the proper monitoring, storage, use, and cleanup of the mixtures. Different states and organizations around the world provide clear guidelines for spill management. [84-86.] A comparison of several guidelines show that the contents of these documents are very similar. Thus, one of North America’s leading energy infrastructure companies, TransCanada, suggests the following fundamental action plan for one of its projects [85]:

- Environmental inspection
- Compounds adequate storage and use
- Transportation safety
- Sufficient sorbent and barrier materials supply
- Comprehensive leak reporting.

The paper emphasizes contractor’s primary responsibility for spills of hazardous compounds and provides more specific requirements for pollution prevention or cleanup, as well as reporting [85]. For the bridge analysis system prototype, each the five categories when compared to local guidelines can award 2 points in the pollution prevention parameter. Nevertheless, if a spill occurs, the pollution prevention parameter is to be assigned 0 in score.

The construction supply chain is a highly complex and diverse conjunction of parties involved in the delivery of goods that satisfy the needs of the project [87]. Sustainable construction supply chain management accentuates fair treatment of people and regard to ecology, evolving both social and environmental aspects. According to Pang et al., there are five principle measures for accomplishing a sustainable supply chain: green initiative, cost price, production process, customer service, research, and development. [88.] LEED v4 also raises special attention to the social equity for the supply chain workers. Requirements for fair treatment of employees in LEED v4 cover such aspects as no child involvement in the process, health and safety right, fair working hours and pay, non-discrimination, as well as harassment intolerance and grievance procedures. [89.] In the supply chain activity analysis, the satisfaction of each factor brings up the score of the supply chain parameter with 1 point, summing up to a total of 10 points.

4.2.4 Sustainability Factor Maintenance and Access

Recently, the public's attention is attracted to the accessibility of the built environment. In the first place, accessibility refers to the creation of a comfortable and obstacle-free environment for disabled people. Although in most of countries new structures are required to be designed with regard to accessibility, conversion of old structures into accessible ones can be a problem. So far, many of disabled people cannot easily move in urban areas, thereby being constrained from various activities available to other members of the society. Mostly, built environment accessibility for disabled people concentrates and provides guidelines on the building sphere. Nevertheless, infrastructure accessibility is proven to be a more complex and substantial problem. However, some municipalities, such as the city of Toronto, provide handicapped accessibility guidelines for the bridges in particular. [90; 91.] Thus, the parameter for accessibility for the disabled can be assigned a maximum of 10 points in the assessment system if comprehensive and suitable approachability practices are implemented in the design. If such guidelines are not implemented, the parameter score is 0 points. If the bridge is not meant for pedestrians, for instance, in case of most railway bridges, points meant for the accessibility parameter are referred to the parameter for accessibility for maintenance. That is suggested due to the higher traffic load on such bridges and, therefore, higher need for orderly supervision and maintenance.

Another type of bridge accessibility is related to maintenance. Generally, bridge maintenance encompasses preventable maintenance, inspection, and further required renovation activities [92]. The main purpose of maintenance is to ensure further serviceability and reliability of the structure. However, some design procedures can have an adverse impact on the future inspection and maintenance procedures. [93.] It is a highly sophisticated task to check all the aspects of structure accessibility during the design phase. Out of that fact, two problems can be distinguished. First, maintainability design is not integrated in the structure's function design. Second, existing methods based on professionals' expertise are not sufficient alone. In addition to authorized guidance on accessibility design, various studies recommend implementing Virtual Reality (VR) tools for maintenance design and execution phases. VR has proven to be effective for the elimination of lags and a multitude of accessibility issues already during the design stage. As for the inspection period, a professional can, for instance, compare the existing structure to the 3D model of the design. Thus, higher legibility of the situation is granted with lower time costs. [93-95.] If the authorized design guidelines for maintenance accessibility are used in the structure design phase, 10 points are awarded for the accessibility parameter. If virtual reality is efficiently implemented in both design and inspection phases, 10 points are awarded in the virtual reality parameter. If VR is implemented in either design or inspection, it is to be awarded 5 points.

Another advanced technology recently introduced to the bridge maintenance domain is a Structural Health Monitoring (SHM) system [96]. SHM represents a variety of data acquisition devices, a data transmission system, data management database, data modeling and analysis, condition analysis and performance prediction, user interface visualization, as well as an operating system and software [97]. In brief, the system is designed to carry out a multitude of visual inspections and to combine that with reliable sensor data. As a result, high precision data is collected in real-time and effectively analyzed afterwards. Though the cost of system implementation is relatively high, SHM has been shown to be effective in the long-term. [95.] Therefore, if the SHM system is implemented in the parameter for the structural health of a project is to be awarded 10 points.

One more important criteria within Maintenance and Access SF is the quality of the maintenance plan. To guarantee the reliability and serviceability of a structure, the maintenance plan has to cover project-specific preventative bridge maintenance practices, as well as large-scale renovation activities. Inspections are to be carried out only by professionals who have received bridge inspection training and have been correspondingly examined. The construction maintenance schedule is to be composed on the basis of the project type, scale, and other factors. [91.] The availability of a clear and efficient maintenance plan equals to 10 points within maintenance plan parameter in bridge analysis system.

4.2.5 Sustainability Factor Environment and Atmosphere

As mentioned above in this paper, the construction industry is one of the major contributors of adverse environmental impacts, such as natural resources depletion, various kinds of air and water pollution, global warming, deforestation, and many others. Since the Brundtland Report publication, employment of ecological practices has been growing in importance, especially in the construction sphere. In other words, environmental quality stands for the features that mitigate negative environmental impacts. [96.] Basically, an ecological construction strategy comprises concern for the selection and utilization of materials over lifetime, water quality and efficiency, energy conservation, waste minimization, pollution prevention, and flora and fauna retention. [99.] Except for the water quality matter, the rest of the factors mentioned above are discussed within other SFs. However, as the environmental and atmosphere scope is large, an attempt to cover further principal ecological strategies and practices is made in this chapter.

First, project related personnel frequently fail to collect the necessary ecological data about the area of the project. Thus, highest possible environmental standards are not met. Every piece of project ecological data is specific, but it is possible to make some general recommendations. [100.] For instance, so-called environmental maps could be of a considerable benefit for the further action strategy in addition to a plurality of laboratory analysis. An environmental map consists of three major types of information on the construction activities: relative to human health and nuisance value, relative to aquatic receiving environments (if applicable), and relative to terrestrial receiving environments. As an outcome, real-time situation monitoring and mitigation strategy scenarios are available. [101.] As for more common practices, chemical analysis of water, soil, and the air is required. Moreover, physical properties of soil, as well as the weed and animal data of the area are to be accurately collected. [102.] If each information type corresponds to 2 points, the information collection parameter can be assigned a maximum 10 points in the bridge analysis system.

Another substantial factor for high ecological performance is attention to local environmental decrees and legislation. Nowadays, governments and environmental organizations are actively developing guidelines for environmental practices. Dozens of governments globally have contributed to the enhancement of environmental laws. The most common legislation that AEC professionals must pay attention to are forestry law, animal protection law, underground water law, water resources law, and protection of the atmosphere law. [103.] Evidently, designations and contents of legislations vary from country to country. Nevertheless, the principal subjects of the documents stay the same. If five generic types of local environmental laws are considered within the project, the environmental decree parameter can award 10 points, 2 scores per each document.

As ecological impact assessment and mitigation is a highly sophisticated task, so it is often not enough to obey the environmental legislation for high performance. Thus, a need for environmental consultancy arises. Firstly, qualified environmental experts are to be employed in every stage of the project. [104.] The qualification can be a conforming university degree or expert certification by environmental assessment systems, such as LEED or BREEAM. Though LEED and BREEAM are mostly related to building construction projects, the basic analysis concepts for the entire built environment are similar. Another reason for no strict qualification requirement is the lack of infrastructure and especially bridge sustainability professionals. Another substantial factor is LCA utilization of the project, as it provides comprehensive data for efficient ecological decision making. [105.] Moreover, environmental education and environmental responsibility of the personnel reinforce the ecological concern at every stage of a project. [104.] Furthermore, involvement of independent environmental monitoring party can help to collect up-to-date data for action plan changes and statistics. [106.] Another benefit of environmental mitigation in the project can be achieved if some of the involved parties invest in environmental study. [100.] Therefore, each of the five factors can be assigned 2 points to consultancy parameter, summing up score 10.

In order to cover complicated ecological aspects within the complex construction industry, environmental management policies are to be implemented. It is also important to relate a particular activity to the correct management type. Out of several kinds of environmental management, the five most common can be distinguished: scope management, quality management, communication management, personnel management, and risk management. These management types usually relate more to global operations than to ecological ones, but their implementation has proven to be more effective. [107.] Thus, the employment of each management type corresponds to 2 points within environmental management parameter.

In recent years, several innovative green bridges were introduced around the world. They are notable structures due to new design concepts implemented to preserve the environment. It is clear that the knowledge practices implemented in accomplishment of green bridges are not project-specific and can often be implemented in other designs. For example, wildlife passage consideration in the bridge design could be used to connect ecosystems. The same principle applies to the concept of plant space reservation within the structure. To prevent deforestation and performance minimization, lower surface of the bridge deck can be designed to be located above top level of the trees. Thus, plants located under the bridge are not subjected to clearance. Usually, bridge shape considerations are not adapted to the environment, instead, the environment is meant to be accustomed to the structure. In order to mitigate the adverse effects of the adaptation process, bridge shape should follow the landscape of the area. Moreover, a natural lighting design of the structure should be paid attention to, so that are inhabitants are not disturbed by the new conditions. [108; 109.] Each criterion in the innovation parameter can correspond to 2 points.

4.2.6 Sustainability Factor Energy Efficiency

The built environment is associated with high energy consumption rate and a large amount of CO_2 emissions [110]. Energy demand usually takes place within entire lifecycle of a structure, from site preparation to demolishment [107]. However, to achieve the most considerable savings of energy and to minimize greenhouse gas emissions, the main focus has to be on operational energy savings and embodied energy of the used materials [110]. Unlike the building sector, operational energy consumption of the infrastructure projects is relatively low. When it comes to bridges in particular, primary attention is paid to energy performance of materials and construction activities. [105.] This chapter covers most applicable energy-saving strategies in the bridge projects recognized by researches on energy savings in the construction industry.

First, information and communication activities provide industries with relevant data on energy operations. Effective decision making is not possible without initial data comprehension. In 2007, the United Nations Industrial Development Organization (UNIDO) declared that information represents itself a key element of any industrial energy efficiency program. Therefore, the first step to successful data activity is a collection of reliable data on applicable energy saving systems, policies, and technologies in the local AEC sector. Another weightful factor is employees' education and motivation towards energy saving practices. Moreover, periodic meetings of the parties with an energy conservation agenda are recommended, as well as common energy database development. The last aspect for successful information exchange is detailed reporting of energy performance in the project. [111.] If the five criteria are fulfilled, 2 points per each, the information and communication parameter corresponds to 10 points.

Substantially, development of construction projects towards green performance requires an active development of corresponding technology and techniques. Various studies have confirmed that technical enhancements of energy-related equipment indeed leed to significant reduction of energy consumption. To start with, alternative energy production, such as solar or wind energy, is highly recommended. For instance, the operational energy of a bridge commonly refers to lightning during the night time. Solar energy accumulation with panels and later utilization during the night time can be an alternative to electricity from the grid. During construction, manual work can replace machine work when applicable. Another important objective is the employment of designers and contractors with expertise in the energy field. In addition to that, efficient design and construction methods are to be adopted as effectively as possible. To evaluate the outcomes of the project's energy performance, energy monitoring software development is advised. [111.] Fulfilling each condition satisfaction brings 2 points to the technology and techniques parameter score, summing up to 10 points altogether.

Another criterion for optimal energy efficiency is energy efficiency of construction site equipment and energy demands of the materials. Efficacy development of both has been active in recent years. However, beneficial results are more successful for equipment than for materials. The primary and evident requirement win the parameter is utilization of energy efficient equipment on the construction site, as well as ensuring the minimization of its unnecessary use. Moreover, frequent site equipment energy monitoring has been proven to promote energy use reduction. [111.] Energy performance of the materials was already discussed in chapter 4.2.1 above. It was identified that during the design stage many professionals prefer to over-dimension the structure to provide high safety level, neglecting material utilization rate. For sustainability, it is recommendable to design for optimal material usage with respect to the local structural design codes. [110.] Moreover, the relation of material strength and embodied energy should be optimum, that is “harmonized”. [112.]

Studies and experiences of various parties have confirmed that government regulations and implementations of energy management practices promote significant energy savings. Several countries in the world have developed effective energy policies which benefit organizations and the environment. Essentially, the employment of governmental energy use regulations is a primary criterion in the regulation and management parameter. A systematic energy use review and analysis can be performed on the basis of the guidelines. [111.] Moreover, a project-specific energy action plan should be developed and utilized. An optimal energy supply option is to be considered in addition to energy-aware scheduling. [113.] Each of the five criteria are assigned 2 points within the regulation and management parameter.

As mentioned above, emissions values of greenhouse gas (GHG) are frequently associated with energy-related operations. Most common GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO_x). GHG emissions of a project present themselves clear numerical indicators that can be used for the energy performance analysis. [114; 115.] Therefore, GHG emission reporting is a reliable activity for representation, analysis, correspondent action plan modification, and future statistics reference of project energy outcomes. Five prevalent construction project GHG emissions sources are to be studied: equipment fuel, onsite electricity use, onsite water use, material production, and transportation. [116.] Therefore, five factors with an equal weight within the parameter ensure a total of 10 points.

4.2.7 Sustainability Factor Traffic Efficiency & Alternative Transportation

One of the factors promoting business activities and economic growth of an area is a long-term transport policy that stimulates high-quality services for inhabitants. Improvement of life standards combined with environmental concerns poses new challenges for the transport industry. The solution of the problem is a set of composite measures. However, the most important aspects for beneficial outcomes is the use of alternative (or green) transportation means along with traffic efficiency management. Commonly, green transportation emphasizes bicycling, regular public transport, rail transport, as well as walking. When it comes to environmentallyfriendly vehicles, green transportation encompasses, for example, electric vehicles, natural gas vehicles, solar energy vehicles, and others. Traffic efficiency refers to satisfaction of transportation demand with the local transportation system. [117; 118.]

Biking is a green transportation method that many bridges can promote. LEED v4 category bicycle facility for buildings can be successfully interpreted for bridges as well. First, design of the structure itself has to include bicycle trail, or an access point to the nearest bike track is to be located in a 180m radius of the bridge. Moreover, the facility should have a bicycle storage facility in its vicinity, at most at a distance of 30m. [119.] If both criteria are satisfied, the bicycling accessibility parameter can be assigned 10 points in the analysis system. Another environmentally beneficial transportation type, public transport, can also be maintained by the bridge. According to LEED v4, access to quality transit recommendations, at least one public transportation stop should be found within 800m from the facility. If the condition is satisfied, the public transportation parameter is 10 points.

To contribute to both traffic efficiency and green transportation development, a bridge feasibility study is to be carried out. On the basis of the environmental and socio-economic situation of the area, the decision for the most beneficial bridge location is to be made. A feasibility analysis along with its consideration of its outcomes brings the project 10 points for the feasibility study parameter in the bridge analysis system. [44.] To further provide efficiency development of transportation, digital transport control system utilization is favorable. Such a system allows real-time monitoring and operation control of bridge-related traffic facilities, such as traffic lights. If this criterion is fulfilled, the transport control system parameter is 10 points. [44, 120.] To increase the traffic safety and security of the area, a continuous safety monitoring system, managed by a central traffic control, is to be installed. For railway bridges, a similar track safety monitoring is recommended. [44.] If accordingly accomplished, road safety monitoring parameter gains 10 points.

4.2.8 Sustainability Factor Sustainable Site

A sustainable site can be defined as a project location area that is maintained according to sustainable practices during construction and construction preparations, that provides itself an environment for sustainability-driven functions upon its completion. When designing a green construction project, professionals should first consider an environmentally appropriate site that will secure the balance between serving people, nature, and economy. [121.]

The selection of the location of the bridge site is substantial. Bridges are usually constructed when the need for passage arises in a particular area. Nevertheless, if constructed in a wildlife habitat, the bridge may disrupt the ecosystem. Thus, the preference can be given to two categories of sites: previously developed land and brownfield, or previously contaminated land. For brownfield, remediation is to be completed before construction in accordance with local legislation. Thus, construction project may be environmentally beneficial for an area in the gross. Previously developed land can be acknowledged as such if 75% of it is proven to be subjected to human activities recently. [122.] If either brownfield or developed land selected for a project, the points for the location parameter in the bridge assessment system are equal to 10.

According to LEED v4 for new structures, the sustainable site is to be associated with greenfield area preservation and restoration to promote biodiversity and habitat protection. If there is no greenfield in the area, adapted or native vegetation is to be planted on the site, thus restoring habitat environment. In some cases, the need for soil import arises. If so, the quality of the imported soil is to be ensured and its extraction must not adversely affect its area of origin. If qualitywise satisfactory greenfield at the project site, the main objective is to preserve the largest percentage of the original greenfield area. Overall, as an outcome of the project execution, at least 40% of the site is to pertain to the grassland area. [123.] If the condition is fulfilled, the habitat protection or restoration parameter awards 10 points.

One more criterion for site high sustainability performance accomplishment is ensuring outdoor open space. The target is to promote an open-air passive recreation, physical activities, social interaction, as well as interaction with the environment. LEED v4 requirement is reservation of at least 30% of the total site area for open space. Essentially, the outdoor space is to be physically accessible and to include a pedestrian-oriented paving or turf area. As an alternative, space is to represent itself as a garden space. [123.] If the criterion is satisfied, the open space parameter is to gain 10 points in the analysis system.

Due to human activities and consequent heat emissions, urban areas are warmer than rural ones. This phenomenon is called an urban heat island effect (HIE). It causes an adverse impact on the microclimate and, subsequently, on the inhabitants of the area. First of all, the HIE lowers the quality of water and air, because it creates a more suitable environment for various types of pollutants. In the summertime, the HIE contributes to higher air conditioning demands which lead to a significant increase in energy consumption. [123.] To mitigate the negative effects of HIE on the environment, LEED v4 recommends the use the following roofing principle [123]:

$$\frac{Area\ of\ nonroof\ measures}{0.5} + \frac{Area\ of\ high-reflectance\ roof}{0.75} + \frac{Area\ of\ vegetated\ roof}{0.75} \geq Total\ site\ paving\ area + Total\ roof\ area \quad (1)$$

If the condition is satisfied, the Heat Island Reduction parameter is assigned 10 points in the bridge assessment system. Sustainable bridge site operation is not possible without efficient and environmentally oriented waste and stormwater management. Generic ecological waste disposal principles encompass optimal environmental performance of any vehicle involved, proper vehicle access to the site, adequate storage areas, which together provide a basis for waste recycling. A stormwater management plan is required to maintain natural water circulation and to avoid an early structure deterioration. The management plan must be developed in accordance with the local legislation. [122.] If two management systems are designed and implemented in the operation phase, the waste and stormwater management parameter in the analysis corresponds to 10 points, 5 points for each management system.

4.2.9 Sustainability Factor Equity and Social Issues

When it comes to social performance of bridge projects, there is still no clear assessment criteria, as the subject is not yet studied in detail and existing views on it differ. Thus, social performance of a bridge is recommended to be evaluated together with the larger scope of transportation infrastructure criterion at the moment. [44.] According to publications between 2001 and 2017, social criteria emphasis in infrastructures was varying. However, most weighty criterion covers the following aspects within the recent 16-year period: safety, accessibility, local economic development, and employment. Similar to other SFs, the analysis of the parameters is complex and includes many indicators. [124.] Nevertheless, an attempt was made in this thesis to evaluate the situation on the whole on the basis of the key issues.

Essentially, user safety of bridge structures is one of the primary indicators of social performance. Safety is a critical issue to be covered over a project's entire life cycle, which includes safety concerned design, monitoring, and other procedures. [44.] Nevertheless, to obtain a numerical value for user safety during the operation phase of a project, Navarro proposes the following formula that includes the characteristics, transport speed, as well as maintenance time of a bridge [125]:

$$X_{user's\,safety}^{maintenance} = 1 - \frac{l}{L_{tot}} * \frac{\sum t_m}{T_{SL}} * \frac{v}{V_{norm}} \tag{2}$$

Where l – length of the maintenance work zone,
L_{tot} – total length of the bridge,
T_{SL} – service life of the bridge,
$\sum t_m$ – total time that the bridge is under maintenance,
v – traffic speed under maintenance operations along the work zone,

V_{norm} – traffic speed under normal operation conditions.

If $X^{maintenance}_{user's\ safety}$ equals to 1, the safety parameter of the bridge assessment system gives 10 points. With each 0.1 drop, criterion is to lose 1 point.

Another important social aspect of a bridge is its user accessibility. Accessibility is one of the demonstrative indicators of socio-economic growth of an area, although is complex to measure. Infrastructure accessibility generally covers the availability and the quantity of transportation, as well as remoteness of all the other services. [124.] However, Navarro introduces a simplified bridge numerical evaluation of user accessibility as a relationship of bridge availability, maintenance, and lifetime [125]:

$$X^{maintenance}_{accessibility} = \frac{(T_{SL} - \sum t_m) * 1 - \sum t_m * a}{T_{SL}} \tag{3}$$

Where T_{SL} – bridge service life,
$\sum t_m$ – total time that the bridge is under maintenance,
a – bridge availability, which is the ration between traffic speed under maintenance and normal operation circumstances.

If $X^{maintenance}_{accessibility}$ equals to 1, the accessibility parameter of the bridge analysis 10 points. With each 0.1 reduction, the parameter is to lose 1 point.

A bridge should encourage local economic development by connecting economic activities, improving transportation quality, and reducing travel time. Local economic development by construction project also encompasses several categories. Some of them, such as material procurement, were studied previously in chapter 4.2.1 Sustainability Factor Materials and Resources. However, to measure the output numerically, Navarro suggests the use of Gross Domestic Product values:

$$X^{activity}_{local\ economy} = 1 - \frac{gdp - GPD_{min}}{GDP_{max} - GDP_{min}} \tag{4}$$

Where gdp – Gross Domestic Product at the activity location,

GDP_{min} – minimum national Gross Domestic Product,
GDP_{max} – maximum national Gross Domestic Product.

If $X_{local\ economy}^{activity}$ is larger than 1, the economic development parameter of the bridge analysis system is assigned 0 points in the analysis system. Starting from 1, with each 0.1 decrease, the parameter is to be assigned 1 point.

A bridge construction project provides employment opportunities which are of high significance for social operation. On a large scale, infrastructure projects encourage employment during their execution and operation phases. Nevertheless, it is more complex to assess the operation phase employment, because infrastructure is often one of a plurality of factors impacting the employment situation. [124.] Therefore, it was decided to pay primary attention to the employment situation during the design and construction period of a project. Two of the most important criteria of the employment situation in the area are the employment rate and the salary grade. [125.] According to Navarro, the local employment and salary fairness situation can be measured with the following formulas:

$$X_{local\ empl.}^{activity} = \frac{ur - Ur_{min}}{Ur_{max} - Ur_{min}} \quad (5)$$

Where ur – unemployment rate at the activity location,
Ur_{min} – minimum national unemployment rate,
Ur_{max} – maximum national unemployment rate.

$$X_{salary}^{activity} = \frac{s - S_{min}}{S_{max} - S_{min}} \quad (6)$$

Where s – mean salary for the specific activity at the activity location,
S_{min} – national living wage,
S_{max} – maximum national salary for the specific activity.

If $X_{local\ empl.}^{activity}$ is equal to 0 or less, the local employment parameter is assigned 10 points in the analysis system. If the result is 0 or lower, the parameter is to lose 1 point with each 0.1 gained. If $X_{salary}^{activity}$ equals to 1 or higher than that, the fair salary parameter is awarded 10 points in the bridge assessment system. Starting from 1, the parameter is to lose 1 point with each 0.1 reduction.

4.2.10 Sustainability Factor Pavement Technologies

Road pavement is one of the most common forms of transportation infrastructure that affects the social, economic and environmental spheres. To maintain pavement serviceability, large financial and resources investments are required. An improperly designed and maintained road pavement is subjected to early deterioration, which leads to an increase in costs and to various types of emissions of pollutants. There are several common types of pavement used in the world, each with their performance characteristics and maintenance requirements, their strengths and weaknesses. [126.] This chapter concentrates mostly on prevalent road pavement sustainability, taking into account that road bridge pavement is possible to adapt to railway bridges with certain modifications. [127.] An attempt is made to distinguish the most common aspects of pavement sustainability with a literature review. As a result, five substantial criteria are highlighted: employment of recycled materials, adequate maintenance, noise level, stormwater runoff, and traffic prediction. [128-131.]

In all urban regions and between them, pavements are indispensable, so their demand for materials and resources is immense. To mitigate the ecological impacts by depletion of natural resources and improper waste disposal, recycling was introduced to the pavement engineering industry. As stated above, material recycling is one of the basic principles of sustainability and circular economy in particular. Several studies have confirmed that polymer waste products of other industries, such as rubber and plastic, can be successfully implemented in pavement construction. Moreover, asphalt, often utilized in pavement construction, is a fully recyclable material. Nevertheless, due to mechanical properties of the recycled materials, generally up to 30%-40% reprocessed content can be used in the pavement construction at the moment. [132-134.] If the pavement material consists to 40% of recycled aggregate, the material recycling parameter is awarded 10 points in the bridge analysis. With each 4% decrease, the value loses one point.

The significance of adequate maintenance of pavements is often underestimated, although it actually has a major impact on product performance and the environment nearby. It is not always possible to make up for insufficient design and construction with maintenance. Nevertheless, maintenance is to endorse pavement serviceability if properly executed. Maintenance involves efficient planning and scheduling, development of guidelines, people's safety, as well as proper and environmentally conscious execution techniques. There are no universal sustainable maintenance requirements for pavement maintenance, as their characteristics vary. If maintenance is planned with respect to the factors mentioned above, and no early wearout occurs, the maintenance parameter can be awarded 10 points in the bridge analysis system. [135.]

Other considerable criteria for pavement performance are the ambient environment and the noise disturbance the pavement causes to inhabitants. The noise level associated with paving is to be mitigated optimally. A primary solution to the nosie problem is choosing the material in terms of noise performance. For instance, noise reducing surfacing can be implemented. It is important to note that the noise performance quality of pavement decreases over lifetime. The measure of noise efficiency is so-called rolling noise which is generated by wheel-pavement interaction, its unit is dB(A). The noise level of an operating road is to be measured at a defined distance, usually around 15m from the road. The sound is measured on a logarithmic scale, so several noise sources do not result in a proportional performance degree. For instance, if two sources of sound, each 70dB(A), are added up, the outcome value is not 140dB(A) but 73dB(A). As a result of a rough estimation, a 82dB(A) level will be achieved with 16 analogical sound sources. Therefore, traffic congestion in the area may have a highly perceptible effect if route passability is high and the scale of the highway is large. Typically, the sound level of pavings varies from 70dB(A) to 120dB(A). [136-140.] If the pavement sound performance of a bridge during a typical traffic density period is 70dB(A) or lower, the noise parameter is assigned 10 points. With each 10dB(A) increase, 2 points are deducted.

Water quality is another descriptive indicator for sustainability performance of pavings. Paving can impact, both directly and indirectly, the quality of groundwater and, consequently, nearby ponds of the area. During and after construction, pavement can transmit potentially hazardous residual substances to the ground. Moreover, paving can transfer road operation byproducts into waterways during its operation phase. In addition to that, if subjected to excess of moisture, pavement deteriorates, leading to loss of strength and durability. As a result, extensive maintenance or even replacement is required. This results in a notable cost increase and adverse environmental effects. Therefore, properly designed stormwater disposal and filtration system in conjunction with the rainwater disposal system of a bridge are to be installed to support the sustainability of a bridge project. [141; 142.]

Constant growth of the traffic flow on both highway and railway networks contributes to rapid paving deterioration. As mentioned above, maintenance is of high importance for pavement serviceability prolongation. Currently, pavement inspection schedules are under development and, furthermore, do not take into detailed consideration of the wearing mechanism due to vehicles. If this can be predicted, the result would be a notable growth of maintenance quality and efficiency. Moreover, such a practice could be highly beneficial for bridge design as well. Therefore, the thesis includes a traffic prediction parameter in Pavement SF. Various mathematical models, such as the Markov decision process, can be utilized to forecast traffic. [143.] If such a model is employed, the traffic prediction parameter is assigned 10 points in analysis system.

4.3 BIM-based Bridge Sustainability Analysis Software

As had already been stated, BIM can provide a plurality of opportunities for successful sustainability-oriented decision making at the very early project stages. Thus, it allows high action flexibility throughout a project with considerable cost and time savings through various simulations and analyses of project outcomes. Sustainability evaluation is complex, because it encompasses a great number of aspects from various disciplines. Currently, IFC is the most advanced non-proprietary data exchange format which has a potential to be utilized in such sophisticated assessments in the AEC sector. It grants not only an information exchange tool, but also a solid basis and classification system capable of manipulating highly complex construction project information. At the same time, sustainability rating systems are the sets of criteria to be achieved during and after the construction phase. To succeed in this, an early integration of any design processes and criterion rating systems is indispensable. The use of IFC in combination with sustainability criteria allows improved data extraction and its further elaboration, ensuring dependable outcomes with less endeavor. In other words, BIM software covers data from a variety of fields and related activities. IFC, as a customizable information format that encourages openness between the involved parties, has the capacity to gather and operate data effectively. It can be utilized for sustainability-oriented analysis. Based on chosen rating system criteria, a computer program that operates data within the IFC can be written. [51.]

Currently, several assessment packages for cost, labor, energy, and comfort performance of the built asset are available on the market. BIM-based sustainability assessment is able to facilitate sustainable development within the industry, as it allows to make an optimal choice between multiple design alternatives at the early stages of a project. Moreover, most the forecast reports provide information about further implementation and development of BIM-based analysis tools, which will evidently promote the expansion of application areas of evaluation packages. Generally, the analysis process engages some kind of data exchange between the model and the analysis tool. Recently, several studies on the conjunction of BIM software and green building assessment systems have been carried out. In every study, data for sustainability analysis was either added to the model, or the model was augmented into sustainability assessment data that is capable of storing complementary information. [144.]

Several studies on BIM for sustainability assessment were recently carried out. In an attempt to integrate LCA and BIM, Ahmad Jrade and Raidan Abdulla developed a prototype of an LCA tool that is linked to a BIM model. The prototype is designed to perform the LCA on a simple Autodesk Revit 3D-model by employing IFC as an information exchange standard. One of the study's purposes was to reach the highest possible automation level of LCA execution, i.e. the minimization of mandatory manual information collection about materials and processes used in the manufacture and assembly of construction products. A wall and a door were modeled in Autodesk Revit. After that, the model was exported as an IFC file and with IFC file analyzer represented as a text document. Further, the data from the document was replicated in the spreadsheet application Microsoft Excel. A ruleset for data extraction and analysis was composed and utilized as a computer program. In such a way, information from Microsoft Excel file was collected, converted, and input in the respective LCA tool spreadsheet, covering multiple LCA criteria. The experiment of Jrade and Abdulla was successful. [145.]

Another study on BIM for sustainability assessment was conducted by Sebastiano Maltese and others. They provided a concrete example of daylight assessment process for a BIM model with respect to LEED, BREEAM, and CESBA requirements. For all rating systems, daylight criteria encompass an illuminance calculation of the surface at a specific time, and a daylight factor range calculation at frequently used areas. First, the rating system criterion and final report structure were defined. Second, related IFC parameters such as Illuminance, visible transmittance, and solar transmittance were explored. The parameters were connected either to IfcSpace, IfcElement or IfcMaterial objects, which refer to a specific property set, such as Pset_MaterialOptical. Then, a web service was required to automatically extract data from IFC file, to fill the report template, and to analyze the sustainability performance of the construction project. [51.]

On the basis of the work of Jrade and Abdullah and Maltese et al., it can be concluded that the IFC data format can be utilized for model analysis of the environmental sphere of sustainability. Nevertheless, it is important to note that there are limitations during the assessment, presently confining the concept to a feasibility study. First of all, the definition of the link between criteria fulfillment of the rating system and current IFC data structure may be sophisticated. Secondly, IFC does not contain some considerable assessment system factors, which requires manual creation of new IFC property sets. The issue has the potential to be solved by the future IFC standard expansion. [51.] At the moment, the standard is under development and IFC5 release is expected in the near future. [146.] As can be seen from the IFC data model, it encompasses information related not only to the environmental aspects of a project but also data associated with the social and economic sides of a project. If it is possible to do the environmental assessment with IFC data, social and economic analyses can be carried out accordingly. [51; 145.] Nevertheless, as sustainability covers three extensive dimensions, sustainability assessment of a construction asset is to be limited by the structure type and related sustainability criteria.

Based on Maltese et al. [51], IFC-based bridge sustainability evaluation process generally consists of the following main steps:

1. Definition of the rating system requirements and final report layout
2. Development of a service able to automatically extract necessary data from IFC file

3. Creation of a final report
4. Creation of an application that fills the report with data extracted from IFC

First of all, the object related parameters of a bridge sustainability assessment system are to be defined within IFC. If no relevant object or parameters exist, one has to be created as custom. The same applies to properties and property sets. After that, the software has to extract text information and analyze the properties of a project on the basis of the sustainability evaluation criteria presented above in chapter Bridge Sustainability Assessment System. Then, the final report template is compiled and filled with the data gained in the analysis. [51; 145.] An example of the final output can be found from appendix 5.

5 Conclusion

The final year project presented in this thesis was carried out to study BIM and the possibility to apply it in bridge sustainability analysis. The literature review reveals a great focus on sustainability in the building industry, while the sustainability of infrastructure, and specifically bridges, is not yet concentrated on. In the thesis, it is elaborated that BIM, as a potent tool, provides the platform for integrating sustainability principles into the bridge design. This can especially be achieved with a specialized type of software. For successful accomplishment, the instrument is to be primarily implemented during the design phase of a project, so that the involved parties are allowed to operate with higher quality data and, further, select the most viable action alternatives. In other words, the construction, execution and operation circumstances of a construction project are predicted to the highest possible credibility and compared to the sustainability rating system criteria. The sustainable development principles are implemented in order to benefit ecology, people, and business.

The thesis shows that IFC, as a BIM interoperability standard, has a potential to present itself as an analysis platform for the sustainability evaluation of bridges, although it still lacks many properties. Thus, IFC requires a large number of custom parameters for an even more detailed sustainability analysis performance. However, there is a practical opportunity that it can be successfully employed in sustainability analysis of various construction projects as it expands. A sustainability evaluation system can provide a dynamic assessment of multiple scenarios of interaction of sustainability factors. On this basis, optimal decision making can be performed with respect to three main spheres of sustainability. Furthermore, an IFC Bridge standard can be even more useful for bridges in particular.

When it comes to BIM-based assessment software for bridges, the first aspect revealed during the final year project was a lack of particular generic criteria for broad sustainability factors, such as environment and atmosphere or energy efficiency. Thus, there is still a need to further develop a universal evaluation system of bridge sustainability that would be widely recognized by environmental experts and bridge engineers. Furthermore, the thesis established that numerous measures depend on the region, its climate, local guidelines, and other issues, valid solely for a specific area. Thus, it is strongly recommended to consider the development of a locality-oriented analysis system.

The evaluation system presented in the paper is semi-automated, so it still requires human verification at some points. Thus, more diversified parameters with more numerically perceived information are recommended to be utilized in the IFC to elaborate the process automatization. In addition to universal bridge criteria, it is recommended that local guidelines are implicated in software operation and updated later. Moreover, the framework needs to be further explored for the accreditation of project-specific innovation solutions, which are now common among sustainability practitioners. Another challenge to be faced is that information is required from multiple disciplines, also outside of the AEC industry. Thus, the thesis recommends that a highly accessible cloud-based system is designed and implemented, so that each party involved can smoothly input information in the IFC. Similar systems already exist and are developed at the moment, but they are not yet generally used, and they are intended for AEC professionals only. Thus, large digitalization investments are required to make such a move. However, sustainability principles implementation and processes automatization have proven to be highly beneficial in the long term.

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Sustainability Considerations within Penang Second Bridge Project

Table 5. Sustainability consideration in P2B.

Code	Sustainability factors	Summary of sustainability considerations in P2B project
SF1	Materials and resources	• Optimisation of the usage of higher reinforcement ratio and amount of concrete by using the high strength concrete with silica fume, PFA and GGBS cement. • Reduction in waste material, energy consumption and cost through using precast SBG. • Use of alternative materials and composites. • Solves the seismic design issue through application of HDRB made up of natural material and requires minimal maintenance throughout its lifetime and conserves the environment. • The cable stayed and the parallel pattern type allow for a slim section, enable for long-span bridge, better performance, better construction methodology, faster project execution, cost optimisation and no need for anchorages to sustain strong horizontal forces. • Reducing the raw materials by use of precast SBG. • Use of local construction materials, except for the cable-stayed saddle and anchorage, and steel fender. • Cathodic protection system and special coating for tubular steel piles and steel fenders for protection against corrosion. • High strength concrete with GGBS and PFA for the pile cap, pier column, crosshead and SBG to prevent sulphate and chloride attack that can cause corrosion to the reinforcement bar. • Euro-code Standardised Concrete cover to protect the reinforcement bar against corrosion. • Inspection and Test Plan (ITP) and Method Statement to identify the inspection and testing status of purchased construction materials and works carry out on site.
SF2	Project delivery process	• Project breakdown into smaller sub-projects. • Concurrent Engineering Approach. • Supervising the quality of works. • Design and Build contract for Package 1 and 2 to reduce the delivery schedule by overlapping the design phase and the construction phase.
SF3	Construction Activity	• Maintenance dredging to ensure that the depth was sufficient for the movement of segmental box girder barges. • Use of SGB; all the segments were delivered by barges to their places for installing; the production line casting of SGB is in a controlled environment. • Ship impact load criteria assessment of the Bridge to discover that the Bridge could resist any accidental ship impact. • Bridge is calibrated with tsunami event. • Despite all the construction activities around the bridge's pillars, having minor impact on the profound environment of the bridge, they have some positive impact on the environment such as piles driven become heaven for fish and marine life. • Application of IBS design: repetitive use of formwork, machineries could count as the reuse planes of this project: sections including tubular steel piles, precast spun piles, reinforcement caging, precast shell and SBG are IBS components that are prefabricated on land to reduce the amount of time spent on the bridging line and the risk of damaging or polluting the marine environment. • Construction of Second Penang Bridge is a prescribed activity under Activity 9(c) of EIA Order.
SF4	Maintenance and Access	• Design for minimal maintenance. • Application of Structural Health Monitoring (HSM) System.
SF5	Environment and Atmosphere	• Environmental monitoring through environmental consultants to monitor dredging and disposal of spoil, and regime through EIA, EMP and the FIA. • Environmental Quality Act and Regulation under the Department of Environment. • High standards of environmental protection are incorporated into the project while consultants are closely monitored to avoid changes to the sensitive marine environment. • Minimal impact on water flow. • Green Building Technology. • Reducing the impacts of dredging. • Habitat creation.

SF6	Energy Efficiency	• Consuming the minimal total embodied energy by approving the higher reinforcement ratios and less concrete with adopting the HSC. • Design of SBG to optimise reinforcement ratios and concrete. • Application of HPC with silica fume and PFA cement to give the durability required. • Elastomeric bearing have a low embodied energy per m^2 of the bridge deck. • A green building concept is introduced for Toll Plaza and Administrative Building Complex which is taken up to save water, energy and material. • Energy dissipation materials and facilities such as Steel Box Buffer System, HDRB and precast SBG. • Cut energy use approach through air pollution reduction compared to traffic jams at the First Penang Bridge and usage old ferry transport across the straits.
SF7	Traffic Efficiency and Alternative Transportation	• Traffic control system (Surveillance System). • Selecting the best possible location in the Project feasibility study. • Traffic reduction by removing the unnecessary driving among the First Penang Bridge. The bridge is expected to reduce traffic on the First Penang Bridge by 20% and will transform Penang into key logistics and transportation hub for the northern region of Malaysia under the Northern Corridor Economic Region (NCER) programme and Growth Triangle comprising Indonesia, Malaysia and Thailand (IMTGT). • Lane configuration dual 2 lanes traffic, emergency lane and 1 motorcycle lane each direction. • Road safety system to control and managed 24 h a day by a central traffic control and monitoring and Closed Circuit Television (CCTV) installed at the toll plazas, interchanges and strategic locations along the expressway. • Implementation of multi-lane free flow system to reduce traffic congestion at toll plazas as the system allows free-flow high-speed toll system. • The bridge will serve as a catalyst for development at the northern corridor and also position the state as a transportation hub for the northern region.
SF8	Sustainable Site	• Supervision to monitor the construction progress at site and for public. • The proposed site lies within a seismically stable region. • Supervision the construction works. • Emergency Response Plan. • Promotes sustainable site vegetation that does not require irrigation. • The landscaping and the exterior look of the Toll Plaza are designed in such a way that the trespassing light is eliminated by plants and shaded area.
SF9	Innovation	• Construction methods. • Lateral pile load tests. • Articulation. • Seismic isolation. • IBS system and minimal maintenance concept in planning, design and execution. • Renewable energy by humps to generate electricity, rainwater harvesting tank and wind turbine at Surau minaret for additional power supply.
SF10	Water Quality	• Environmental monitoring and auditing works for overall water quality (EIA monitoring). • Marine water quality during construction of load out jetty at disposal site (Marine Water Quality Standards). • River water quality (National Water Quality Standards). • Reconnaissance assessments of the water quality at areas of fisheries and aquaculture importance.

(*continued*)

Table 5. (*Continued*)

Code	Sustainability factors	Summary of sustainability considerations in P2B project
SF11	Equity and Social Issues	• Provide job opportunity for the local contractors, consultants and workers. • Application of a comprehensive risk management approach. • Attracting the local prawn and other marine life. • Safety and health monitoring through inspection and audit approaches, such as Project HSE Plan, the Occupational Safety and Health Act (OSHA, 1994) and Factory Machinery Act (FMA, 1967). • Noise-level monitoring (EIA approval conditions and permissible sound level according to land use category). • Protective fences or walls at the edge of a bridge to prevent vehicles on the bridge crashing over the edge and also give protection to other vehicles and motorcycles. • Doing a safe work by minimising the work at height and over water by using the precast technique of the numerous parts of Bridge in the land (SBGs) are the socio-culture aspects of this project.
SF12	Pavement Technologies	• Asphaltic concrete deck pavement, road signage, road marking and related road furniture (excluding TCSS, IT IS and VMS). • Construction of flexible pavement complying with the specified International Roughness Index (IRI). • Pavement IRI Index: 2 m/km. • Flexible pavement works. • Installation of guardrail, road pavement markings and road signage.
SF13	Custom Credits	• This factor is come up with an idea for a design/construction best practice for project that is not currently included in other factors, such as: • Integrated toll system. • Conventional form of contract. • Vocational training. • Regional economic development. • Green building technology for proposed toll plaza and administrative building complex. • Flora and Fauna monitoring. • Habitat creation. • Dust control. • Sewage and sullage water management. • Waste management. • Value engineering/design optimisation. • Precast concrete shells for: minimisation of temporary works, minimisation of *in situ* works, speed of construction and better surface-finishing works. • Slip form system (slip form is a self-climbing formwork that once set up as a desired shaped wall to be built, it ascends continually to the height of the structure). • Best Management practices at site

BIM applications withing AEC industry

Table 3 40 case studies and 13 main BIM uses in academic publications

Purpose to use BIM	Project type	Highlights	References
Procurement	Industrial Research and Development project	Integrating BIM model-driven architecture, service-oriented architecture, and cloud computing may challenge e-procurement	[45]
Sustainable design and analysis	Salisbury University's Perdue School of Business building	Establish the relationship between BIM-based sustainability analyses and the LEED® certification process; documentation supporting LEED® credits may be directly or indirectly prepared using the results of BIM-based sustainability analyses software	[17]
	Student housing complex	Develop a novel parametric approach that integrates climatic and site data into a dynamic model of a large building project, to support architectural decisions in early design stages	[25]
	New Community Emergency Service Station (CESS) facility	Develop energy efficient building design process using data mining technology which can help project teams discover important patterns to improve the building design	[58]
	Headquarters building	BIM can significantly aid in performing complex building performance analyses to ensure an optimized building design	[16]
Safety design and management	Residential building	Develop a rule-based automatic safety checking of construction models and schedules on top of a commercially available BIM platform	[109]
	Hong Kong TKO Sports Ground	Develop a virtual prototyping (VP) -based safety management system in large-scale construction projects	[50]
	School building	Propose a framework for a novel safety management and visualization system (SMVS) that integrates BIM, location tracking, augmented reality (AR), and game technologies	[77]
Design alternatives selection and optimization	High-rise building structures	Develop a structural building information modelling (S-BIM)-based design procedure to increase the efficiency of selection and obtain more optimal solutions to eventually improve the constructability, structural safety, and economic feasibility of the building	[62]
Operation and maintenance	EV building of Concordia University	Integrate BIM and RFID for fire equipment inspection and maintenance	[68]
	Campus building	BIM-based facility management for maintenance planning	[7]
	Environmental Research Institute building	Virtual sensors for estimation of energy consumption and thermal comfort in buildings with underfloor heating	[79]
	Fire House	Present a new serious gaming approach based on BIM for the exploration of the effect of building condition on human behaviour during the evacuation process	[83]
	Taiwan school	Develop a BIM-based Facility Management system for facility managers and staffs	[89]
Supply chain management	Building project in Carrollton, Georgia, "The School of Nursing at the University of West Georgia"	Integrate BIM and Geographic Information Systems (GIS) into a unique system, which enables keeping track of the supply chain status and provides warning signals to ensure the delivery of materials	[56]
Construction planning and management	70-story office building	Use Construction Virtual Prototyping (CVP) to integrate product, process and resource models of construction projects so as to support construction planning in virtual environment	[63]
	Building project located in northern Taiwan	Propose an interface system that uses the BIMs ability with regard to quantity take-off of required materials (such as steel, forms, and concrete) to support site-level operations simulation, ultimately leading to the generation of a project schedule	[99]
	John Molson School of Business (JMSB) at Concordia University	Integrate BIM and RFID for progress monitoring and lifecycle management of the Heating, Ventilation and Air Conditioning (HVAC) components	[68]

Table 3 continued

Purpose to use BIM	Project type	Highlights	References
	Steel structure	Integrate BIM and RFID for optimization in steel construction	[105]
	Building at Leader University in Taiwan	Present a scheduling system that applies multi-dimensional (MD) CAD model, Object Sequencing Matrix (OSM), and genetic algorithms (GAs) to generate the time–cost integrated schedule for the construction project	[40]
	National Stadium, Guangzhou West Tower, and Qingdao Bay Bridge	Develop a BIM and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction	[55,108]
	Worcester Trial Courthouse	Use BIM in construction logistics and progress tracking	[84]
	Industrial building	Present a combined method for automated construction activity monitoring system, which consists of three components: an automated activity tracking subsystem based on image recognition, an automated material tracking subsystem, and a mobile computing supported communication environment	[81]
	United Kingdom hospital	Develop BIM-enabled tools to allow site workers using mobile tablet personal computers to access design information and to capture work quality and progress data on-site	[35]
Quality management	Plant facility and its office building attachment	Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data	[11]
	Campus building	Use BIM and laser scanning for quality assessment	[91]
Automated building design review	US Courthouses	Development of space database for automated building design review systems	[61]
	Capital facility	Develop a safety code compliance checking technology that does not replace human judgment, but supports human decision making of safety experts, designers, engineers, and field staff	[110]
	Residential house	Present a new integrated approach to automated code compliance checking for building envelope design based on simulation results and building codes	[90]
Fabrication	Residential building	Develop a new BIM-based tool for design and prefabrication	[69]
	Medical pavilion	BIM-enabled design-to-fabrication on building delivery	[28]
	Airport	Use BIM for design, fabrication and erection	[44]
	Residential facilities	Establish a methodology for the automation of design and drafting for the building manufacturing of residential facilities based on the platform construction framing method	[8]
Information integration, management and visualization	Engineering project in the campus of National Taiwan University	Propose an application framework to effectively solve the problems of integrating project information and system interfaces among different participating parties and engineering application systems, as well as to provide five kernel modules to encapsulate complicated management and visualization functions	[103]
Cost management	Teaching building project	Develop a BIM-based construction cost estimating application software	[65,111]
	Teaching building project	Establish an IFC-based construction product information model of cost estimation	[65]
		Formulate a general process map and the involved key algorithms for semi-automatic and specification-compliant TBP cost estimation based on the IFC data of the design model	
	Reinforced concrete structure	Use BIM for quantity take-off	[23]

Table 3 continued

Purpose to use BIM	Project type	Highlights	References
Commissioning	Building	BIM-enabled building commissioning and handover	[104]
	Environmental Research Institute (ERI) building Cork	Multi-dimensional building performance data management for continuous commissioning	[5]
	Mary General Hospital	Identify several benefits of Implementing BIM for Healthcare Facility Commissioning	[22]

BIM implementation case studies

Type	Project name	Year	Phase	Uses
Bridge	Twin Span Bridge in New Orleans, USA	2005	Design	Design reviews Design authoring Structural analysis Data storage and sharing Visual demonstration Collaboration
	Bridge of Lions rehabilitation in St. Augustine, USA	2009	Plan design	Plan review comments and permit processing Mechanical analysis Load analysis Stress analysis Geometry analysis
	South Kasheli Bridges in India		Design	Structural analysis Mechanical analysis Live load analysis Verification of consultant's design
	The Sutong Bridge	2007	Design	Design checking Structural system and parametrical analysis Stage analysis
	New Jubilee Bridge in India		Design	Civil superstructure analysis Design visualization documentation Alignment
	Marina Bayfront Pedestrian Bridge in Singapore		Design	Civil structural analysis Design Documentation Geometry modelling
	Hoover Dam Bypass Project		Design	Design visualisation Environmental analysis
Road	ProjectWise Online Connects aeCOM With 12 sub-consultants in 22 Offices	2009	Construction	Web-based communication platform for DB contract Work sharing Content reuse Dynamic review File management Quality control Document storage
	State highway in Austin, USA		Design	File management, Quality control Quality assurance Document control Collaboration

Type	Project name	Year	Phase	Uses
	NysdOt Pilot Project in New York	2008	Design construction	3D modelling to minimize environmental impact
				Coordination platform
				4D schedule
	LJB, Incorporated West Broad Street Columbus, Ohio		Construction	3D laser scanning point cloud
				3D site map
				Human error eliminate
	MD 2/4 Southern Connector Boulevard Lusby, Maryland		Design	Design modelling Coordination platform
	Highway 155, Canada		Design	3D simulation
				Volume measurement
				Verification of right-of-ways
Airport	New Bangalore International Airport in India		Design	Civil site Design Design Evaluation
				Information exchange
				Integrated design
	Huston's George Bush Intercontinental Airport		Design construction	Existing condition modelling
				3D design model
				3D model walkthroughs
				Design review
				Prepare final coordination and pipe fabrication drawings
				4D schedule simulation

Developed bridge sustainability rating system

Most relevant sustainability area(s)	Sustainability factor	Parameter	Condition to achieve maximum score
Environmental	Materials and Resources	Recycled content	100%
		Contaminants emissivity	0%
		Renewable period	10 years or less
		Energy consumption	0.1MJ/kg or less
		Durability	10 types of durability are satisfactory
Social, Economic	Project Delivery Process	BIM adoption level	Level 3 BIM adoption
		Timeline consideration	No delays
		Skills and education	Design party's education PhD or average experience at least 15 years (combination possible)
		Transparency	7 construction information types available
		Fair employee treatment	100% of satisfied workers
Environmental, social	Construction Activity	Waste management	100% of construction waste recycled
		Transportation reduction	Supplier's location within 50 km from the site
		Area disturbance minimization	Mitigation plan implemented for each disturbance type (10 in total)
		Pollution prevention	Action plan fully taken into account, no spills
		Supply chain	10 factor satisfaction
Social	Maintenance and Access	Accessibility for disabled	Guidelines for disabled approachability are implemented
		Accessibility for maintenance	Guidelines for maintenance accessibility design
		Virtual Reality	Efficiently implemented during the design and use phases
		Structural health monitoring system	Implemented in a project
		Maintenance plan	Effective maintenance planning
Environmental	Environment and Atmosphere	Information collection	5 common information types
		Environmental decree	5 legislations
		Consultancy	5 factors
		Environmental management	5 practices
		Innovation	5 practices

Most relevant sustainability area(s)	Sustainability factor	Parameter	Condition to achieve maximum score
Environmental, economic	Energy Efficiency	Information and communication	5 practices
		Techniques and technology	5 strategies
		Equipment and materials	5 considerations
		Regulations and management	5 strategies
		Greenhouse gas emissions reporting	5 reports
Environmental, social	Traffic & Transportation	Bicycling	Parking and trail access
		Public transportation	Public transport stop not further than 800m
		Feasibility study	Completed
		Traffic control system	Present
		Road safety monitoring	Present
Environmental, social	Sustainable Site	Location	Brownfield or previously developed area
		Habitat protection or restoration	At least 40% of the site area is a greenfield
		Open space	At least 30% of the site area
		Heat island reduction	Roofing condition satisfied
		Waste & stormwater management	2 efficient plans provided and applied
Social, economic	Equity and Social Issues	Safety	Condition satisfied
		Accessibility	Condition satisfied
		Economic development	Condition satisfied
		Local employment	Condition satisfied
		Fair salary	Condition satisfied
Environmental, economic	Pavement Technologies	Material recycling	40% recycled content
		Maintenance	Comprehensive maintenance plan, no wearout
		Noise	70dB(A) or less
		Water quality	Stormwater runoff system
		Traffic prediction	Mathematical prediction model implemented

Bridge sustainability analysis software output example