Hindawi
Advances in Civil Engineering
Volume 2020, Article ID 8842113, 18 pages
https://doi.org/10.1155/2020/8842113

Review Article

Special Issue "Digital Twin Technology in the AEC Industry"

Jisong Zhang,[1] Lihua Zhao,[1] Guoqian Ren,[2] Haijiang Li,[2] and Xiaofei Li[3]

[1]*School of Civil Engineering, Dalian Jiaotong University, Dalian 116028, China*
[2]*Cardiff School of Engineering, Cardiff University, Cardiff CF24 3AA, UK*
[3]*Institute of Road and Bridge Engineering, Dalian Maritime University, Dalian 116026, China*

Correspondence should be addressed to Guoqian Ren; reng@cardiff.ac.uk

Received 30 July 2020; Revised 20 October 2020; Accepted 11 November 2020; Published 27 November 2020

Academic Editor: Qian Wang

Sustainable building design has become a hot topic over the past decades. Many standards, databases, and tools have been developed for achieving a sustainable building. Not until recently have the importance of structural engineering and its contribution to sustainable building design been full recognised. However, due to the highly fragmented and diversity of knowledge across building and infrastructure domains, there is a lack of approach that can address all the sustainable issues within the structural design. This paper reviews the sustainable design from the perspective of structural engineering: (1) reviewing the current situation; (2) identifying the gaps and difficulties; and (3) making recommendations for future improvements. The strategies and indicators, as well as BIM-enabled methodology, for sustainable structural design (SSD) are also discussed in a holistic way. The results of this investigation show that most of the methods are not doing well in terms of delivering a successful sustainable structural design. It is expected that the future BIM could probably provide such a platform to address these issues.

1. Introduction

What is a "sustainable building?" Written works define it as being designed to adhere to several objectives: (1) to preserve energy and materials and ensure that resources are recycled and that the release of toxic substances is limited throughout the building's process, encompassing the design, building, functioning, preservation, and destruction; (2) to suitably comply with the local environment, values, and societal structure; and (3) to maintain and enhance the standard of people's living whilst preserving the ecosystem's aptitude domestically and globally [1]. This definition brought together what is now known as the three pillars of sustainability [2–4]: environmental, economical, and social well-being. In general, design methods for achieving a sustainable building are called "sustainable design."

There are many standards, databases, and tools dedicated to sustainable design in the building sector. The standards including ISO/TC 59/SC 17, ISO/TC 207/SC 5, and CEN/TC 350 lay the foundations for assessing the sustainability of a building during the life cycle. These standards measure the influence and elements of buildings in terms of their environmental, social, and financial impact via quantitative and qualitative signs [5–7]. In most cases, these series of standards are merely served as guidelines and need to be used in conjunction with a specific database or rating score system since they provide little information on benchmarks, levels of performance, and detailed information [8]. Several databases currently exist for the measurement of embodied energy or embodied carbon: Inventory of Carbon and Energy (ICE), U.S. Life Cycle Inventory (LCI), GaBi, European Reference Life Cycle Database (ELCD), and Ecoinvent [9, 10]. In order to automate the sustainability assessment of a building, many companies and international organisations have initiated rating systems and tools to facilitate the assessment process. The rating systems such as BREEAM and LEED group the environmental impacts into several sections, produce an overall score for the building depending on points gained in each section, and deliver a certificated assessment [11–13]. However, these assessments are normally conducted after the design phase and serve primarily as a verification document rather than a decision-aid tool, providing little guidance for the designer during the design process [14, 15]. Despite the emerging life cycle assessment

(LCA) tools (i.e., Athena and Tally) provide more opportunity to assist sustainable design on a building scale, the procedure is similar to the rating systems (i.e., sustainable assessment after the design stage). It seems difficult to integrate sustainability idea/knowledge into the early design stage. This forces us to rethink of the nature of the building design process.

A building is better expressed as a process than a product. The design process of a building normally requires effective and close cooperation among different disciplines (i.e., structural engineers, architects, and MEP engineers). Architects can start drafting architectural designs once they know the needs of the consumer, the tone and idea of the design, and the core mechanical requirements. The models devised outline the relevant geometrical aspects and appearance of the building. At times, this is accompanied by a range of recommendations regarding the structure; this is compiled into either a model or a drawing of the building's design. Emphasis will then be given to the structural and MEP consideration. The structural engineer is required to make the designs more straightforward so that the model can be structurally analysed and optimised to improve the structural performance. This iterative mechanism ceases when the aims of the design are fulfilled [16]. Ultimately, the structural models, architectural models, and MEP information need to be assembled together for the purpose of sustainability assessment. The above describes the current sustainable design process, a "bottom-up" process, while a more reasonable procedure should be a "top-down" process where sustainability is considered at an early design stage for each engineer [17]. This poses a challenge to planning and handling the process properly.

On the contrary, the type of structural system is a significant aspect because it sets the foundation for the design and building work that is undertaken; the nature of the structure layout significantly impacts the use of land, resources, and energy, the release of greenhouse gas, preservation, recycling, the cost of the process, and the management of risks [18, 19]. Moreover, the structural material accounts for a large proportion of a building's mass, thus providing over 50% of the embodied energy and carbon of a building [20–22]. However, despite this growing awareness, there is scant evidence that the importance of a structural engineer has been sufficiently recognised. Structural engineers do, however, have less influence over a building's sustainability in comparison to architects and clients. This can be due to the fact that the knowledge of sustainability for structural engineers is highly fragmented, and there are no clear guidance and effective tools to assist structural engineers for performing sustainable design [23, 24]. Some studies focus on methodologies, strategies, and parameters for sustainable structural design. For instance, Anderson and Silman [25] investigated the differential impact of material selection, recycling, adaptability, and thermal mass effects on greenhouse gas reduction. They identified that the thermal mass effects contribute a lot to reducing carbon dioxide emissions, and material selection is the most positive design strategy before the operational stage of a building. Danatzko and Sezen [26] discussed five positive and negative sustainable attributes of sustainable structural design methodologies. They suggested that no single methodology can address the complex issues of sustainable structural design, and a combination of the methodology is recommended. More details are discussed in Section 3.2.

Several researchers pay attention to compare the case study by calculating embodied energy or carbon of a structure. For example, Sinha et al. [27] performed a comparative study for calculating the energy footprint and carbon footprint between the wooden building and concrete building. The results indicated that the energy footprint of the wooden building is 43% lower than that of the concrete building, and the carbon footprint of the wooden building is 75% lower than that of the concrete building. Guggemos and Horvath [28] compared the environmental effects between concrete and steel-framed structures (much of the same layout) over the life cycle. During the construction phase, compared to the steel structure, the concrete structure consumed more energy, CO_2, CO, NO_2, and SO_2 due to the large formwork, longer equipment uses, and more materials to be transported; thus, minimizing the amount of temporary material use is an effective way to reduce the impact. However, when expanding the construction phase to a wider range (i.e., entire life cycle including design, construction, use, and end of life), the differences gradually disappear due to the fact that the use phase accounts for over 80% energy use and CO_2 emissions over the life cycle, whatever material is used in the frame structure. Catherine et al. [29] analysed 200 building structures from the industry to benchmark their environmental impact. The normalised material weights for all the structures were 200–1800 kg/m^2, and normalised embodied CO_2 ranged between 150 and 600 kg CO_{2e}/m^2.

In theory, these methodologies and strategies can be used for sustainable structural design (SSD) [30, 31], while in reality, they have not been utilised effectively in a holistic way. This can be attributed to several reasons. Firstly, unlike the sustainable design approach for architects, there are no exclusive standard, database, and tools specifically designed for structural engineers to achieve a sustainable structure. Secondly, the structural engineer's tools, such as structural analysis software, sustainability assessment software, and BIM software, exist as separate entities. Despite there exists the interoperability that is based on interoperable languages (i.e., IFC and gbXML), the process for converting the format is a time-consuming task and may lead to data loss at times. Lastly, there is a lack of effective collaboration between architects and structural engineers. Generally, most of the tasks related to sustainability belong to architects who represent the whole design team to communicate with the sustainability consultant. It should be recognised that not only architects but also structural engineers have great potential to reduce the environmental impact over the design process [32–37]. The ultimate goals of sustainable design can be achieved by efficient information exchange and effective collaboration between structural engineers and architects. A central repository, namely, common data environment, would contribute to the high level of cooperation. In this case, there is a need to have a unified platform that can integrate sustainability considerations within a common environment between designers.

Building information modelling (BIM) involves a standardised process that ensures relevant data and expertise are reused across various fields in the life cycle process. BIM has the trend for constantly growing to utilise the wide array of information that comprises a conventional building project. This information, referenced as being *n*-dimensional (nD), incorporates elements including time, expense, sustainability, and potential risks. As with several other nD building elements, incorporating the issue of sustainability into BIM is yet to be fully developed [38–40]. Currently, there are many methods that can integrate sustainability issues into BIM or conduct sustainable assessment based on the BIM models [41–44]. For example, Ilhan and Yaman [45] extracted the IFC data from BIM models and proposed a green building assessment method for assisting designers in the generation of documentation for obtaining green building certification based on the BREEAM category. The method can automatically calculate the green rating and provide feedbacks to inform the design. Shadram et al. [46] identified the lack of interoperability between BIM and LCA tools and proposed a framework to integrate extract, transform, load (ETL) into BIM to enhance BIM-LCA interoperability and thus enable a semiautomated assessment process. Although structural engineers can use these methods for making a rough sustainable assessment of their design, these methods are specifically tailored for architects or clients. From the structural engineering perspective, several attempts have been made to combine BIM, structural analysis, and LCA or develop API to accomplish structural sustainability appraisal in BIM [47–49]. Yet there exist many papers on green BIM or structural optimization, most of them have several steps for conversion among different formats, the commonly accepted (standardised) procedure is lacking. Currently, BIM software is still a long way from being fully integrated with various databases for the sustainable design project. Better and more seamless integration between BIM and sustainable design may come in the future, but currently, the integration requires considerable effort and time such that the evaluation of sustainable data ends up being performed after the design stage in most cases.

As a result, this paper attempts to fill the gap by reviewing sustainable design with emphases on the structure. The specific objectives are (1) to investigate the current situation of sustainable design, especially sustainable structural design; (2) to identify the challenges and problems associated with integrating the sustainability issue into structural design; and (3) to discuss solutions and potential development for achieving a holistic design. The review consists of mainly two parts: in the first part, a comprehensive investigation of the standards, databases, tools, and software regarding sustainability in the sustainable building design domain is identified through a wide range of sources. The emphasis is put on the aspects that are directly related to the structural design. In the second part, the current statuses of sustainable structural design (SSD) are investigated with emphases on the strategies and indicators. Furthermore, the BIM-enabled methodology for achieving a sustainable structural design is also summarized. The challenge that sustainability-BIM integration faces is discussed, and the solutions to this incorporation are proposed for future improvements.

2. Sustainable Design for Buildings

2.1. Standards. Over the past decades, a significant number of sustainable design approaches for buildings have been developed by diverse organisations throughout the world. The term “sustainable design approaches” in this paper refers to all the standards, databases, and tools regarding sustainability in the building design domain. The history of sustainability towards standardization can be traced back to 1993 when a standardised approach called the “code of practice” was developed by the Society of Environmental Toxicology and Chemistry (SETAC) [50]. The approach divided the sustainable assessment into a three-step process, including the definition of the goal and scope of the LCA, the Life Cycle Inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase. The International Organisation for Standardisation (ISO) attempts to provide an additional definition of this in the mid of 1990s. A series of LCA criteria was then defined or updated by the ISO including Subcommittee 5 (SC 5), Technical Committee 207 (TC 207), and Life Cycle Analysis and Environmental Management. In 1997, based on the three-phase process proposed by the SETAC, ISO 14040 was released by incorporating the “life cycle interpretation” phase into the criteria. Since ISO 14040 provides only the principle and framework without describing and specifying any detailed LCA methodologies and techniques, ISO 14041, ISO 14042, and ISO 14043 were produced with the aim of providing strategies of the methodological basis during 1998 and 2000 [51, 52].

Yet, this criterion is only aimed to provide a universal approach for LCA practice and hence does not correspond with the extensive judgements needed in relation to modelling when conducting an LCA. As a result, the standards proposed by ISO/TC 207/SC 5, ISO identified that the broad array of possible implementations for LCA needed field-specific Technical Committees to provide an additional definition of LCA that incorporated the expert opinion of those working in the area. As a result, Subcommittee 17 (sustainability in building and civil engineering works, SC17) was developed under TC 59 (buildings and civil engineering works) to produce numerous criterions that provide additional definitions of the LCA framework. Therefore, various criteria and guidelines (ISO 21929, ISO 21930, and ISO 21931) were produced under the direct command of ISO/TC 59/SC 17.

The ISO standards outlined above are regarded as the standard international outlook regarding LCA conduct. However, the necessity for a consensus has resulted in the ISO failing to consider certain modelling aspects that are needed for standardised LCA practice. For that reason, the European Committee for Standardisation (CEN) Technical Committee 350 (TC 350) was introduced in 2005, aiming at ensuring LCA standards being developed for building works. EN 15643, EN 15804, and EN 15978 were established under CEN/TC 350 by considering more factors in regard to the preservation of the environment. In a similar way to ISO/TC 59/SC 17, CEN/TC 350 started by placing its emphasis on guidelines for buildings rather than civil engineering, although TC 360 has of late implemented Working Group 6 (WG 6) that is intended to advance guidelines for the future that are relevant to civil engineering. All the aforementioned standards are summarized in Table 1 with more detail.

The biggest challenge for the standard is that there is a lack of reliable, comparable benchmarks and transparency in the methodologies. The results of building assessment are not comparable to one another. Furthermore, the above series of standards are used as frameworks or guidelines for sustainable design since they do not provide benchmarks, levels of performance, and detailed information, which need to be used in conjunction with a specific database or score system. Whilst LCA is an important mechanism for contemplating the influence of judgements in terms of the system, it is the only one mechanism that should be utilised for considering sustainability from a wider perspective. The limitation of LCA concerns its generic Life Cycle Inventory (LCI) datasets that overlook the viability of special and temporal matters. For instance, "land use" is seldom incorporated into LCA as there are no means of recording it within an inventory that is widely recognised. Studies into LCA have delivered significant process in introducing acknowledged ways of measuring land, water, waste, and flows that happen over a range of locations and times.

2.2. Databases. During the LCA process, the inventory analysis is an important step since the LCI database gives the basic data for life cycle assessment. In recent years, there has been an increasing amount of databases worldwide that can be used to carry out an life cycle assessment. These databases can be divided into two types: general database and specific database. The difference between the general database and specific database lies in the data coverage. General database refers to the data that may cover many fields (e.g., transportation, agriculture, manufacturing, building, chemicals, and waste management), whereas the specific database in this paper means that they are targeted for only one field (i.e., building or construction). General databases contain the European Life Cycle Database (ELCD), U.S. LCI, Swiss Ecoinvent, and German GaBi [53–55]. Specific databases include the Inventory of Carbon and Energy (ICE) from UK, Canadian Athena, Australian building products LCI, and New Zealand building material embodied energy database [56, 57]. The specific databases are normally designed for the life cycle assessment of a building. Table 2 gives a nonexhaustive summary of the LCI database around the world.

The biggest challenge for the database is inconsistencies in the data source, which means that the use of different databases leads to a comparison issue. For much the same as the layout of a building, the results from SimaPro, GaBi, and ICE show significant difference due to the lack of reliable and transparent data. There is a demand for a reliable database to be provided by the manufacturing and construction industry. Furthermore, there is still a need for updated values for different countries and regions. As a result, it is likely that, in the future, LCI records will provide the necessary data for the analysis of life cycle impact within LCA research. Moreover, the LCIA stage needs to be spatially and temporally broad to collage the flows happening within the life cycle. There is a need for updated values per country as most of the databases have not been updated with progression of time. As far as the structural aspect is concerned, there are no standards and databases specifically designed for structural engineers. However, this is not a barrier to deliver a successful sustainable structural design since the environmental impact of a structural material can be obtained from these databases.

2.3. Tools. The term "tools" in this paper refers to the rating systems and software related to sustainability in the building design domain. Generally, tools to perform environmental impact assessment can be divided into three levels [58–60]: (1) level 1: product or component level tools, such as SimaPro, BEES, Gabi, Umberto, and TEAM; (2) level 2: building level tools assisting design decision-making, such as Tally, Athena, eTool, and Bionova; and (3) level 3: rating system or building, infrastructure, and community assessment tools, such as BREEAM, LEED, Green Star, CASBEE, and SBTool.

Specifically, level 1 considers the resources and elements individually, which are then compiled to devise a life cycle consideration for the building as a whole. Level 2 contemplates the whole building as its initial basis. This could, for instance, be the building's shape, before consideration is steadily given to the selection of resources in walls and frames and suchlike. A whole building's environmental impact can be assessed through the level 1 or level 2 approach. The output indicators of these assessments normally include global warming (kg CO_2eq), sometimes containing primary energy (MJ), acidification (kg SO_2eq), eutrophication (kg NEQ), ozone depletion (CFC-11eq), smog formation (O_3eq), nonrenewable energy (MJ), and renewable energy (MJ). Among these indicators, the global warming, namely, "embodied carbon," expressed in carbon dioxide equivalents (kg CO_2eq), is regarded as the most important factor. The other greenhouse gases can be converted into CO_2eq using conversion factors in order to obtain a common unit for the environmental impact.

It should be noted that the incorporation of BIM and LCA mechanisms within the initial design process is a growing tendency for automating the judgement process based on the outcome. BIM is utilised to uncover the information relating to the building (material measurements) which are subsequently processed within external LCA software or else incorporated "plug-ins" in which LCA can be calculated within the BIM process. The advantages of BIM in the LCA applications include preventing data from being resubmitted manually, enabling analysis to be conducted in real time, improving the assessment of the building overall, and utilising an assessment interface that is accessible to the

Table 1: Summary of sustainable standards and specifications for building design.

	Standards and specifications	Level	Environmental	Economic	Social	Release year
ISO/TC59/SC17	ISO 21929 framework for the development of indicators for buildings	Framework	✓	✓	✓	First version 2006, revised 2011
	ISO/TS 12720 sustainability in buildings and civil engineering works	Framework	✓			2014
	ISO/TR 21932 sustainability in buildings and civil engineering works—a review of terminology	Framework	✓			2013
	ISO 21931 framework for the methods of assessment of the environmental performance of construction work	Building	✓			First version 2006, revised 2010, will be replaced by ISO/CD 21931-1
	ISO 21930 environmental declaration of building product	Product	✓			First version 2007, revised 2017
	ISO 21929-1 sustainability in building construction—sustainability indicators—part 1: framework for the development of indicators and a core set of indicators for buildings	Framework	✓			First version 2006, revised 2011
	ISO 16745 environmental performance of buildings—carbon metric of a building—use stage	Building	✓			First version 2015, revised 2017
	ISO 15392 sustainability in building construction—general principles	Framework	✓	✓	✓	First version 2008, revised 2019
CEN/TC 350	EN 15643-1 general framework	Framework	✓	✓	✓	2010
	EN 15643-2 framework for the assessment of environmental performance	Framework	✓			2013
	EN 15643-3 framework for the assessment of social performance	Framework			✓	2012
	EN 15643-4 framework for the assessment of economic performance	Framework		✓		2012
	EN 15978 assessment of environmental performance of buildings-calculation method	Building	✓			2011
	EN 16309 assessment of social performance of buildings-calculation method	Building			✓	2014
	EN16672 assessment of economic performance of buildings-calculation method	Building		✓		2015
	EN 15804 environmental product declarations-core rules for the product category of construction products	Product	✓			2012
	EN 15942 environmental product declarations-communication format-business to business	Product	✓			2011
	CEN/TR 15941 environmental product declarations-methodology for selection and use of generic data	Product	✓			2010

Table 1: Continued.

	Standards and specifications	Level	Environmental	Economic	Social	Release year
ISO/ TC207/ SC 5	ISO 14040 life cycle assessment-principles and framework	Product	✓			First version 1997, revised 2006
	ISO 14044 environmental management—life cycle assessment—requirements and guidelines	Product	✓			First version 2006, revised 2017
	ISO 14045 environmental management—eco-efficiency assessment of product systems—principles, requirements and guidelines	Product	✓			2012
	ISO 14046 environmental management—water footprint—principles, requirements, and guidelines	Product	✓			2014
	ISO/TR 14047 environmental management—life cycle assessment—illustrative examples on how to apply ISO 14044 to impact assessment situations	Product	✓			First version 2003, revised 2012
	ISO/TR 14049 environmental management—life cycle assessment—illustrative examples on how to apply ISO 14044 for the goal and scope definition and inventory analysis	Product	✓			First version 2000, revised 2012
	ISO/TS 14048 environmental management—life cycle assessment—data documentation format	Product	✓			2002
	ISO/TS 14071 environmental management—life cycle assessment—critical review processes and reviewer competencies: additional requirements and guidelines to ISO 14044	Product	✓			2014
	ISO/TS 14072 environmental management—life cycle assessment—requirements and guidelines for organizational life cycle assessment	Product	✓			2014

Table 2: Summary of sustainable databases.

Database	General purpose database	Construction-specific database	LCA	ECC	EEC	Region
Inventory of Carbon and Energy (ICE)		✓		✓	✓	UK
European Life Cycle Database (ELCD)	✓		✓	✓		Europe
U.S. Life Cycle Inventory (U.S. LCI)	✓		✓	✓		US
Ecoinvent	✓		✓	✓		Switzerland
Oekobaudat.de (German)			✓	✓		Germany
Milieudatabase.nl (Dutch)			✓	✓		Netherlands
French national database			✓	✓		French
Australia LCI			✓	✓		Australia
SimaPro database			✓	✓		Netherlands
Gabi database	✓		✓	✓		Germany
CPM LCA			✓	✓		Sweden
EPD database BBRI (Belgian)			✓	✓		Belgium
ProBas			✓	✓		Germany
Japan Sustainable Building Database						Japan
BEDEC			✓	✓		Spain
Athena database		✓				Canada
New Zealand building materials embodied energy database		✓				New Zealand
Building Products Life Cycle Inventory		✓				Australia

LCA: life cycle assessment, EEC: embodied energy coefficients, and ECC: embodied carbon coefficients.

user. On the contrary, the drawback may lead to data loss and format conversion from different software. Although the industry foundation class (IFC) has been used to enhance interoperability between different software for many years, a more automatic and integrated BIM-enabled LCA method is still lacking.

Level 3 is generally a scoring system that provides comparisons throughout the building industry. It is used to analyse the results for the building overall in terms of the sustainability across the built environment life cycle, from new construction to in-use and refurbishment. This process is to advocate the spread of design processes and to advocate to designers the notion of exceeding the building guidelines in place. They contemplate the product overall to a degree but additionally scrutinise design of the building from the perspective of health elements and the sustainability of the society. It has been suggested that the scoring tool is basically a way of standardising various buildings from the perspective of environmental outcomes. Whilst the rating system might differ according to the specific system followed, there is large consistency in how the system functions. For example, the BREEAM (Building Research Establishment Environmental Assessment Method) was first launched in 1990 by the Building Research Establishment (BRE) in UK. Other rating system such as LEED, Green Star, CASBEE, DGNB, and HQE were developed based on the idea of the BREEAM [61–65]. Among these systems, the DGNB (Germany) is deemed as the latest system that is based on the experience from all the former rating systems, which is called "A Second-Generation Certification System." Its main features include (1) early design stage precertificate, goal definition, and integrated planning; (2) risk management with real transparency; and (3) goal-oriented system. Figure 1 shows all the aforementioned standards, databases, and tools to facilitate understanding.

Yet, assessing these systems critically is beyond the viability of this paper, which instead places its emphasis on how it relates to sustainable structural design. Despite the fact that some of the structural design work is not directly related to the rating system, even reduced use of water in concrete can contribute to the water protection and natural environment by integrating the water collection systems and structural systems. The impact that the design of the structure has on the rating tool incorporates various factors including the use of resources, the structural system that is chosen, the disassembly design, and the dematerialisation. Eight rating systems have been considered within this work to analyse the current contribution of SSD to the rating process and to outline enhancements to them. The analysis considers embodied energy and other potential signs of sustainability for the design structure. The work chooses them for being original, transparent, and extensive. The influence of SSD on rating credits, or in other words, the structural points in the rating system, can be divided into three parts: direct, indirect, and supporting. Taking BREEAM as an example, the full credit is 100 points which contains ten sections: management, health and well-being, energy, transport, water, materials, waste, land use and ecology, pollution, and innovation. Four out of these 10 sections are related to structural design. They are energy (direct), materials (direct), waste (indirect), and land use and ecology (supporting). Thus, the total credits of these four parts are 44 points. Other rating systems can be done in the same manner.

Table 3 outlines the credits connected to structural trades within the process of measuring sustainability, indicating that the average figure of SSD-associated credits was greater than expected at approximately 46% [24, 33, 38]. This can be explained by the fact that the influence that structural design exerts on the rating system credits can be divided into two categories based on the involvement of structural engineers: direct influence and indirect influence. The direct influence

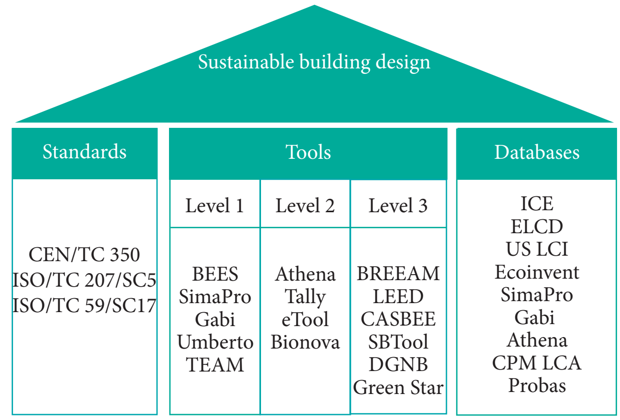

Figure 1: Methods for achieving sustainable buildings.

deals with the material and component level (i.e., material use or cost of a beam and column), while the indirect influence is related to the whole building level, such as shortening the construction schedule, increasing the net height and net area, reducing equipment and labour, and improving the lifespan of a building, which need to be considered accordingly. From authors' point of view, these previous studies have underestimated the contribution of structural design to the rating system credits since they consider only the direct influence. Moreover, there are various rating tools enabling a significantly greater proportion of credits to be ascertained, suggesting that these rating tools provide a greater array of SSD openings to acquire the certification.

Whilst the majority of the research referenced emphasised the limitations of the rating tools in measuring the influence of the design of the structure, the consideration here has identified that the rating methods are fairly progressive in analysing SSD processes, taking into account the majority of issues in this regard. Furthermore, they frequently utilise quantitative measures where they can. These processes give varying significance to various SSD issues based on the area in which they were introduced. For instance, in China, the elements connected to off-site environment are given emphasis, perhaps because the construction process within China is presently especially extensive.

Based on the review of sustainable design approaches for buildings, it can be inferred that the biggest challenge for the standards and databases is the lack of reliable, comparable benchmarks and inconsistencies in databases. Furthermore, the current sustainable design tools typically assess the sustainable performance of a building at a later design stage, thus being a verification or show-off document rather than a decision-aided tool, providing little guidance for designers over the design process. Despite efforts which have been made towards integrating the sustainability issue into the early design stage, no single solution can be reached to come up with a holistic and comprehensive sustainable design. This can be attributed to the fact that there is a lack of efficient approach and tools that can support systematic and effective information exchange between different

Table 3: Summary of the sustainable rating systems for building design (%).

Section	BREEAM (UK)	LEED (US)	Green Star (Australia)	SBTool	DGNB (Germany)	Green Globe (Canada)	HQE (France)	GBAS (China)
Management	11	10.1	9			5	12.5	
Off-site environment					22.5			21
Economical quality				1.3	22.5			
Sociocultural and functional				0.3	22.5			
Technical quality					22.5			
Process quality					10			
Site selection				6.4		11.5		
Indoor environment quality		18.8	17	2		16	12.5	18
Operation and maintenance				26.9			12.5	
Service quality				4				
Health and well-being	14							
Energy	17	18.8	24	19		39	12.5	24
Transport	7		9	13.7				
Water	5	7.3	11			11	12.5	20
Materials (resource)	11	21.7	16	8		12.5	12.5	17
Waste	7							
Land use and ecology	9		5					
Pollution	9							
Emission			9	18.3		5	12.5	
Implantation quality		20.3					12.5	
Innovation	10	3						
Total	100	100	100	100	100	100	100	100
Relevance to structural design	44	47.8	51	27	45	62.5	37.5	61

participants. Furthermore, although structural design plays an important role in sustainable design (score in the rating system), there is scant evidence that the importance of a structural engineer has been sufficiently recognised. The higher percentage of credits offers a great opportunity for structural design acquiring the accreditation of sustainable design. In the next section, the current situations in the sustainable structural design in terms of strategies and indicators will be investigated. The challenges and difficulties associated with integrating the sustainability issue into structural design are also identified and discussed.

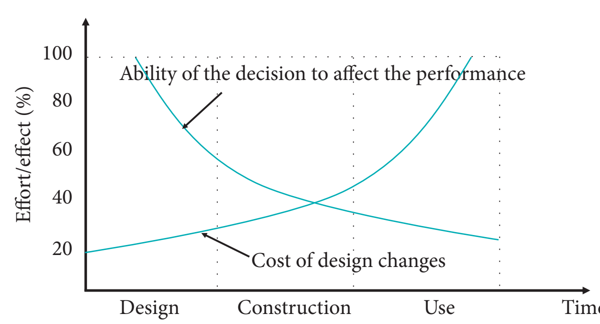

Figure 2: Life cycle stage and its influence on sustainability.

3. Sustainable Structural Design

3.1. General Processes of Structural Design. A building process can be divided into four major periods: design, construction, in-use, and demolition. The design work not only highly influences the overall cost but also greatly affects the environmental impact. The possibility of changing the sustainable performance is high over the design stage and gradually declines as a project progresses (Figure 2). Generally, a structural case—the design of a building, for example—commences with theoretical foundations relating to aspects connected to the structure and the architecture. From contemplation of the needs of the consumers' design, its thematic base and its core mechanical values can enable architects to start drafting resolutions for an initial judgement. This judgement will incorporate self-regulation for preserving cohesion in the design concept, viability tests, and suchlike. When the concepts have been judged to be viable, the extensive stage of architectural moulding will commence. The results of this process outline the relevant aspects relating to arithmetical aspects or its look. These are presented in either model or drawing form. The emphasis will then turn to a structural consideration.

In implementing the model or drawing for the subsequent stage of evaluating the structural design, it is necessary to make the work produced more simplistic so that only the mechanical sentiment is preserved. This might include, for instance, a beam-truss structure within a case made out of a steel frame. This simplified outline can thus be judged for its consistency during this process, and the outcome can be additionally enhanced by altering the structure to maximise the procedure. It is normally expert structural engineers who possess considerable experience and who decide whether a different option is better or if modifications should be made. The state-of-the-art optimization values state that this is a reoccurring stage that concludes once the aims of the design have been fulfilled. Subsequently, additional models or drawings might be suggested for improving the acquisition and manufacturing process. Ordinarily, judging the maintenance of the models proposed also occurs at the subsequent design stage.

Once the acquisition and manufacturing stage has occurred, further alterations can still be necessary due to problems with resources or the construction process. Required alterations to the architectural and structural aspects can be proposed, and the present formation of the design is reviewed. Within the construction stage itself, people asking for alterations is frequent. This can be instigated by a variety of aspects, including the identification of the collision or conflict, and problems with establishing or maintaining the building. This indicates that being adaptable is crucial within the whole design and building process and ought to be given appropriate scrutiny.

3.2. Sustainable Structural Design Strategies and Indicators. It is not the intention of this paper to provide an extensive and deeper discussion on the process of structural design. The focus will be put on the area that is related to sustainability. From authors' point of view, the following aspects should be well understood before the commencement of SSD:

(1) What phase will be considered? (i.e., embodied phase, operational phase, end-of-life phase, or the whole life cycle).

(2) What scope will be considered? (i.e., component level, structure level, or the whole building).

(3) How to quantify the SSD? What are the strategies and indicators? When to perform the SSD? (i.e., early, middle, or late design stage). What tools can be used?

The life cycle phase for SSD can reference the classification of sustainable design, which can be divided into three phases, namely, embodied phase, operational phase, and end-of-life phase (Figure 3). The structural system

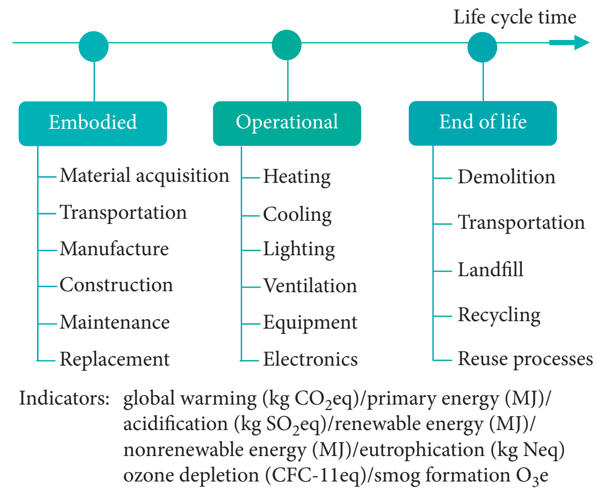

Figure 3: Life cycles and indictors of sustainable design.

contributes a lot to the embodied and end-of-life impacts, not much affects operational impacts. The detail analysis is showed as follows:

(1) Embodied impacts: the structural type ordinarily comprises a significant proportion of a building's mass. Thus, it is a significant factor of the influence on the environment at the beginning stage. Office building LCA research that monitors this indicates that the structure of a building can be responsible for a figure ranging from 30 to 70% of the embodied energy over the construction process. Embodied energy refers to the overall amount of energy used to remove, create, implement, and eradicate a part or system. The vast array is because of various aspects, such as contrasts in the form and scale of a building, the construction sort, and the way in which the structure is defined (impacting upon whether features such as curtain walls are included or excluded).

(2) Operational impacts: from a structural perspective, the influence of structure thermal mass and thermal aspects are the prominent aspects that impact upon the energy results within the functioning stage.

(3) End-of-life impacts: getting rid of structural resources can have a notable influence because of the restricted landfill space and the possible pollution of disposal locations.

It is obvious that the scope of SSD should focus on the component and structure level. The influence of structural design over the sustainability can be seen from two different angles: direct influence and indirect influence. The direct influence deals with the material and component level (i.e., material use), while the indirect influence is related to the whole building level, such as shortening the construction schedule, increasing the net height and net area, reducing equipment and labour, and improving the lifespan of a building, which need to be considered accordingly. On the contrary, these strategies focus only on the material or component level performance, which may result in making the overall building system less sustainable by not considering the relationship and interactions with other parts, or in other words, not in a holistic way (multiperspectives). As such, an all-encompassing strategy that optimises a building's mechanical, financial, ecological, and energy functioning is yet to be fully expanded. For instance, when structural engineers are optimising a beam's height, they are required to judge the impact on the sustainability not only at the component level but also at a building level. The optimum sustainable solution for the slab might not be the optimum solution for the whole building if the optimum solution minimises embodied carbon of the slab and, at the same time, increases the depth of the slab. The indirect influence of optimising a structural component or material on a macroscopic level needs to be considered in a holistic way. Furthermore, some approaches or objectives might contradict other aims relating to sustainability. For instance, restrictions on a structure's carbon and energy might result in the structure's expense being elevated. Any construction projects need to achieve a balance between a lower cost and a higher reliability [66]. This notion can also be applied to the formation of a structural design, meaning that an appropriate arrangement between theories focusing on health and the environment can be reached.

To indicate the correlation between design theories and their influence on sustainability, various approaches have been conducted to categorise them in a natural manner. Danatzko and Sezen [26] suggested that SSD approaches be categorised as indicated in the following: (1) least material condition; (2) minimizing embodied energy; (3) reducing material production energy; (4) performing life cycle assessment; and (5) reuse of the structural system. Yet, the aforementioned categorisations can instigate uncertainty for a variety of aspects. Limiting the utilisation of resources, the production of energy and the embodiment of energy incorporate similarities and can be categorised more specifically. The life cycle assessment is a mechanism used for making a judgement as opposed to being a theoretical approach. Optimising the replication of structural systems incorporates restoration as opposed to a fresh, original assignment.

A further categorisation was indicated by Anderson and Silman [25] which emphasised theories intending to limit the carbon footprint of buildings. They were (1) design for adaptability; (2) design for efficiency; (3) design for energy; (4) design for recycling; and (5) design for materials. This partly linked with the categorisation proposed by Danatzko and Sezen. For example, design for materials corresponds with resources being selected to represent products being used again. This relates in part to the notion of minimizing material production energy. The concept of design for energy partly compares to Danatzko and Sezen's minimizing embodied energy concept, comprising techniques intended to limit the operational energy of the building. Design for adaptability is connected to reusing structures already in ready and devising fresh ones that can be reused subsequently, which is similar to the reuse of the structural system. Webster [36] suggested that the structural engineer can contribute to the environmental impact by using the following methods: (1) use of salvaged materials or the content of the material can be highly recycled; (2) improve the durability of the concrete structure since it would last at least 50 years; (3) improve the adaptability of the structure that can be adjusted over its entire life; (4) efficient use of structural materials towards minimizing the environmental impact; and (5) use of structural materials that can be reused or recycled, and the structural system can be easily disassembled. SEI Sustainability Committee incorporated durability, adaptability, and human health into the SSD method. They reported that durability and adaptability are broad perspectives and are difficult to quantify. The human health much corresponds to the internal finishes rather than the structural design aspect.

Having recognised the impact that the building structure has on the sustainability, researchers and practitioners have investigated the structure performance on the environment from a practical perspective. Several researchers have studied the embodied CO_2 emissions and cost from a structural element level (i.e., beam, slab, and column). For example, Hájek et al. [68] applied the life-cycle assessment methodology to assess the performance of the concrete slab. Three structural floor alternatives ranging from NSC to HPC were chosen for the environmental assessment. They suggested that when evaluating the environmental impacts of concrete structures, a detailed and uniform LCA is greatly demanded. Yeo and Gabbai [69] performed a study for optimising a simple reinforced concrete beam with the fixed moment and shear strengths in terms of sustainable design. The results indicated that in order to reduce 10% of the embodied energy of a beam, the cost will increase 5% accordingly. A further study by Yeo and Potra [70] presented an optimization approach for a structural engineer to evaluate the sustainability and economic objectives. A reinforced concrete frame was used as a case to illustrate the proposed approach. The results indicate the developed approach can reduce carbon emission by 5% to 15%. Foraboschi et al. [71] studied the embodied energy of tall building structures in the range of 20 to 70 stories. The results indicated that the lowest weight of a structure does not necessarily mean it has the lowest embodied energy. The embodied energy largely depends on what type of slab is used in a structure. They also concluded that the steel structure consumes more embodied energy compared to that of a reinforced concrete structure. Gan et al. [72] developed an optimization approach for cost-optimal and low-carbon design of the high-rise reinforced concrete structure by using parametric modelling and genetic algorithm to define the relationship between structural members and the behavior of the entire building structure. The proposed approach can reduce the carbon emissions and material cost by 18–24% after performing the optimization. Weerasuriya et al. [73] proposed a framework to estimate accurately the potential of natural ventilation of a high-rise residential building considering indoor and outdoor air flows, heat gain, and occupant thermal comfort by combining the computational fluid dynamics (CFD) simulation, multizone airflow modelling, and building energy simulation (BES). The results showed that the electricity consumption can be reduced up to 25% by employing winddriven natural ventilation and up to 45% by facilitating the buoyancy-driven natural ventilation.

The most recent analysis of the sustainable structure design was undertaken by Pongiglione and Calderini [24]. They observed the significant elements and stages for undertaking the design of a sustainable structure, which incorporates the desired influence, approaches, and boundaries. Additionally, Bakhoum and Brown [34] suggested a sustainable scoring mechanism to measure structural materials. The tool incorporated reference to various sustainable aspects that impact upon the structural resources that are chosen. Cole and Kernan [67] examined the overall energy utilised in an orthodox 4620 m^2 three-storey, generic office building in terms of varying wood, steel, and concrete provisions. They deduced that the structure can constitute of a sizable element of the energy used within the early stages of a business establishment. Their conclusions verify the findings of other research studies that the structure can be the biggest individual aspect of energy at the embodied stage (Figure 4). For an overview of some of these efforts, refer to the Ph.D. thesis of Hou [74].

Based on the above question and previously reviewed strategies, the classification for methodologies of SSD can be divided into the following parts: minimize material use; minimize global warming; minimize energy; minimize nonrenewable energy; minimize total cost; minimize total weight; maximize material or system reuse; maximize material recycling; and maximize human health. Table 4 shows a summary of strategies and classification method to deliver a sustainable structural design.

On the basis of the sustainable structural design strategies and indicators, a holistic decision supporting the approach that integrates structural design and sustainability issue to assist structural engineer decision-making is needed. In the following section, various methods of incorporating the sustainability issue into structural design through BIM are identified and discussed with the aim of providing insight into the current situation.

3.3. Current Practice of BIM-Enabled SSD. In order to automate the process of SSD, some vendors have developed tools to assess the environmental impact of a structure. The trend is to integrate the sustainability into BIM software. As a prerequisite, the structural analysis needs to be conducted in advance before generating a model in BIM software for the sustainable assessment. Currently, there are several methods that can integrate sustainability issues into BIM or conduct sustainable assessment based on the BIM models [29, 76–80], as follows:

(1) Export the BIM model to external software, normally LCA software, to conduct sustainable assessment, such as IES VE, EnergyPlus, Ecotect, Green Building Studio™ (GBS), SimaPro, Athena EcoCalculator, DesignBuilder, Bentley Hevacomp, and TAS. This process often requires the BIM model to be saved as another format, such as IFC, gbXML, DXF, and Excel. The advantage of this method is that it is easy to use, and the disadvantage of this method includes time consumption and the process is complicated, like a verification document rather than a decision-making tool.

(2) Use of the "Quantity Takeoff or Material Takeoff" function in BIM: the new parameters such as sustainability indicators can be added as project parameters by creating a formula. The indicators such as embodied CO_2 can be calculated by multiplying the mass of the material and embodied CO_2 per kg. The mass of the material can be obtained from "Materail Takeoff," and embodied CO_2 is taken from an Excel format database, such as Bath ICE database. The disadvantage of this method is that some of the parameters need to be extracted from the database manually and input into the Material Takeoff spreadsheet because they sometime mismatch.

(3) Preinstall LCA software within the BIM environment, and connect with a structural analysis tool—this kind of software is like a "plug-in" or "add-in," such as Tally and Environmental Analysis Tool™ (EA Tool™). Compared with methods (1) and (2), this method is more "advanced." The positive attribute of this method is that it allows users to calculate the environmental impacts of the building material directly within the BIM environment right after the completion of the model.

(4) Use of API to accomplish BIM extension [46, 81]: developers depend on a range of techniques to coordinate with the BIM model. For instance, numerous software packages depend on an open file format, including STEP, IFC, and CIS/2. These applications are used to transfer data across various applications. Alternative integrations are found on an impartial database driver such as ODBC, which functions as a converter between different applications. There are many types of programmers that can be used in the Revit platform API, such as C#, VB, SQL, and JAVA. It should be recognised that xBIM is a .NET open-source software advancement BIM toolkit that permits.NET developers the opportunity to access, devise, and monitor BIM models within the IFC format. There is comprehensive assistance for geometric, topological operations and visualisation. Furthermore, xBIM encourages bidirectional translation across COBie and IFC format. Essential libraries for influencing data are all outlined in C#. The prominent element of the geometry engine is produced in C++.

(5) Use of ontology to connect BIM and LCA database [23, 49]: firstly, a LCA database ontology is developed. Secondly, a BIM model is constructed in Revit and exported to an IFC format and then to an OWL format—BIM ontology. Eventually, by combining the two ontologies, a new BIM ontology is constructed and transferred to IFC and then to a BIM model. Overall embodied carbon of the building is calculated through a BIM schedule. The disadvantage of this method is that the ontology for the integration

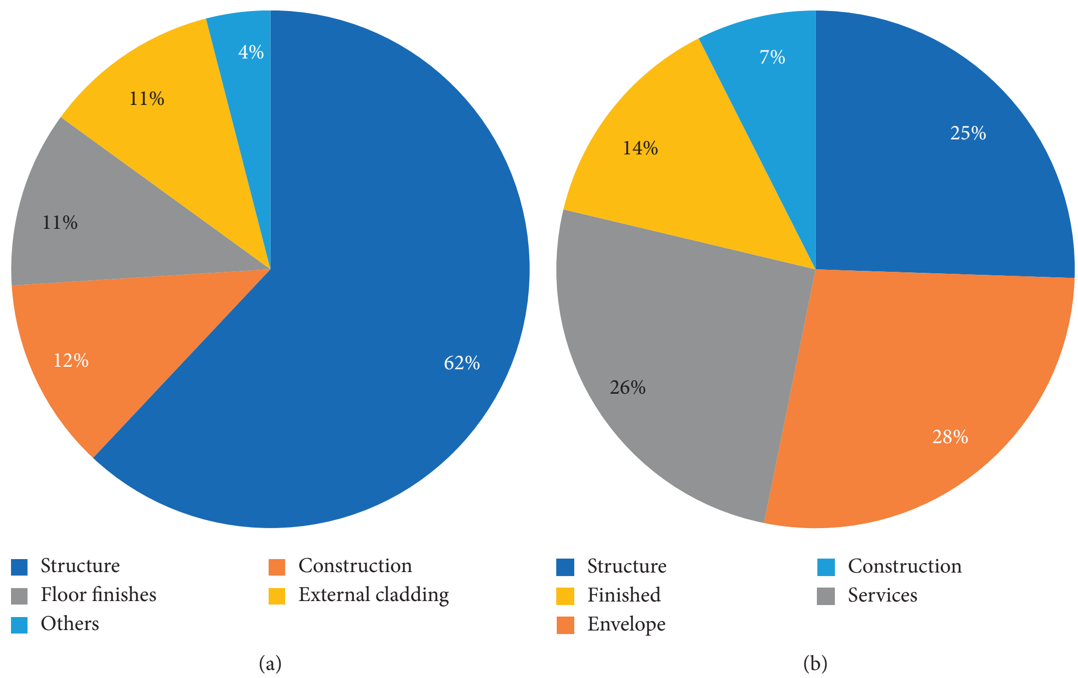

Figure 4: (a) Average embodied carbon in office buildings [22]. (b) Average embodied energy in office buildings [67].

Table 4: Summary of SSD strategies and classifications.

Strategy	Indicator	Scope/level	Embodied phase	Life cycle operational phase	End-of-life phase
Minimize material use [26]	Volume (m^3)/weight (kg)	Material/ structure/building	✓		
Minimize global warming [37]	Equivalent carbon (kg CO_2eq)	Material/structure	✓		
Minimize energy [25]	MJ	Material/ structure/building	✓	✓	✓
Minimize nonrenewable energy [24]	MJ	Material/ structure/	✓		
Minimize total cost [75]	USD/GBP/EUR	Structure/building	✓		✓
Minimize total weight [75]	Weight (kg/ton)	Structure/building	✓		
Maximize material or system reuse [36]	Volume (m^3)/weight (kg)	Material/structure			✓
Maximize material recycling [36]	Volume (m^3)/weight	Material/structure			✓
Maximize human health [35]	VOC (volatile organic compound)	Structure/building	✓	✓	

of the LCA database and BIM is still not fully automated, and importing IFC back into BIM can result in some loss of data. Figure 5 graphically shows the above methods with more detail.

4. Discussion

From the methods mentioned, a number of elements should be recognised. To achieve a sustainable structure, a joint effort is needed to come up with a holistic design both within and outside structural engineers. The challenges that structural engineers face include the following:

(1) A sustainable structural design, allowing consideration of varying aims—including safety, environmental impact, cost, functionality and aesthetics—necessitates an extensive review of the orthodox sequential structural process. Centralisation of different domain information (i.e., structural analysis, sustainability assessment, and detailing software) in a common data environment is a trend. As mentioned earlier in this paper, the interoperability among different software often leads to data loss and difficulties in conversion and change. Additionally, BIM mechanisms presently give restricted assistance in regulating alterations over a

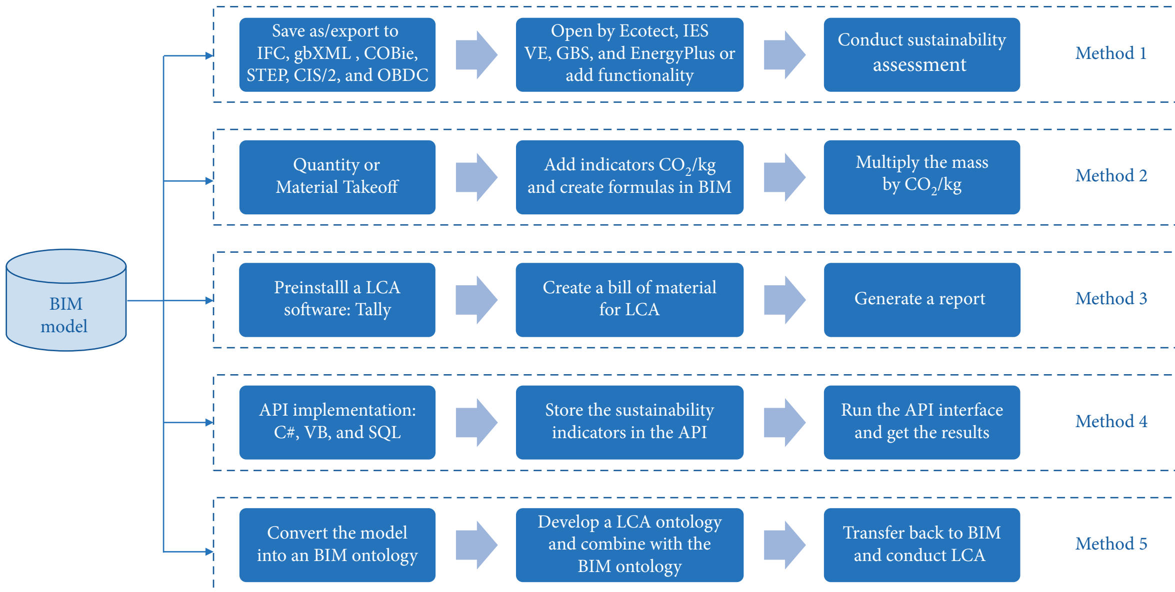

Figure 5: Summary of SSD methods with the integration of BIM.

range of models relevant to a certain discipline. Ontology-based method can be used to reflect, organise, and monitor alterations to design in BIM's context of cooperation over various disciplines. A greater extent of BIM collaboration across varying software is required. The core issue is about multi-objective decision-making in a common environment. It is also believed that semantic web technology and open BIM could probably provide such a platform to address these issues.

(2) Consideration of not only structural material's impact but also impact from structural components and structural form: from the literature review, most of the SSD use the strategies of structural material quantities for minimizing the environmental impact. This, however, is not the only important parameter. For example, from a whole structure perspective, the layout of columns, beams, and slabs also has a significant impact on the overall sustainable performance of a structure. Furthermore, the structural analysis focuses on the material or component level for optimising the environmental impact, which may result in making the overall structure or building less sustainable by not considering the relationship and interactions with other parts. The optimal components are not necessarily optimal for the structure as a whole. A higher degree of impact assessment among different building levels is needed. How to take these factors into full consideration is indeed a challenge.

(3) Strengthened, efficient, and systematic information exchange between architects and structural engineers: a greater engineering response is needed at the initial stage of the design process. However, currently, the architectural model from the architect that aims to deliver to the structural engineer cannot be used directly for the structural analysis. The structural engineer needs to reconstruct the same model from structural analysis software. Although some of the software provided are compatible with BIM tools (i.e., Autodesk Revit), a more streamlined and integrative process is highly needed.

(4) Presently, the majority of structures is devised to limit the embodied influence, as opposed to the overall influence. Minimal advancement in expenses at the initial stage could drastically diminish the influence of the life cycle by reducing the maintenance and permitting salvage or disposal at the process's conclusion. Furthermore, designers ought to try and optimise the adaptability of the design of any structure to permit further alterations in the building's function.

(5) Consideration of the potential influence of the structural material and structural system (form) on the construction and building sustainability, such as lifespan, construction schedule, labour and equipment, and material availability: small changes in initial design could dramatically change the way of construction, which in turn influences the overall sustainability of a building.

It is argued that structural design is not directly relevant to the operational energy use or CO_2 emissions during the use phase, but it has potential influence on the operational phase from the following three aspects. Firstly, the operational CO_2 emissions or energy use can be reduced with the emerging technology over time, but the embodied energy and carbon dioxide cannot be reversed. The structure accounts for the greatest weight in buildings and therefore contributes, on average, to more than half of the total carbon dioxide emissions due to materials. In terms of infrastructure, such as bridges, roads, or stadia, the energy consumption and CO_2 emissions during the operational phase seem rather low, while the structural part (i.e., material production, transport, construction, and demolition) accounts for most of the energy consumption and CO_2 emissions over the life cycle. Secondly, with the effective reductions in operational carbon dioxide of the building in future decades, embodied carbon dioxide will become a more significant percentage of GHG emissions. Some buildings have a short life, resulting in a high percentage of embodied carbon dioxide over the total environmental impact of the life cycle. Thirdly, the structural material selection and the processing and manufacture of structural materials cause enormous off-site impacts prior to the construction or use phase.

The development of a holistic and integrated system becomes an important prerequisite for effective and efficient information sharing and exchange. The fundamental idea of system integration is enabling two or more systems to communicate, share, and exchange information and to interoperate to achieve a common objective. Interoperability, the ability that data generated by one party can be interpreted by all other parties, is the first and most important step towards system integration. Data interoperability focuses on developing common data models, while framework interoperability is achieved by common communication language and protocols. IFC is the most comprehensive international standard for BIM interoperability. Developed and managed by building SMARTIFC, IFC specifies a conceptual data schema and an exchange file format for BIM data, providing a comprehensive description of project structure, physical components, spatial components, analysis items, processes, resources, controls, actors, and context definition. Currently, it has been recognised as the mainstream standard for open BIM and supported by more than 20 vendors. Although the richness of information offered by IFC has been constantly improved since the release of IFC4, the identified barriers to interoperability and applicability include (1) limited expression range; (2) lack of logical formalism that enables rigorous semantics; (3) difficulties in partitioning the information; and (4) multiple descriptions of the same information. The barriers seem to be mainly caused by the nature of the EXPRESS language behind the IFC.

The emergence of semantic web technologies can connect all kinds of information into one semantic web and provide a semantically rich methodology for improving the interoperability by enriching the EXPRESS data. The great advantage of using semantic web technologies is that the schema, the instances, and the rules can all be described using one and the same language. Beetz et al. [82] and Krima et al. [83, 84] discussed that the logic-based language such as OWL can bring modelling advantages in knowledge representation, reuse of existing information, semantic data sharing, and interoperability with semantic web. The initial effort to convert EXPRESS into OWL was made by Schevers and Drogemuller [85]. The developed prototype and mapping create the opportunity to use semantic web-related technologies for building information models. This initial effort was extended by Beetz [86] and Knublauch et al. [87] with proposing a semiautomatic method and system for the conversion from EXPRESS to OWL. Pauwels and Terkaj [88] proposed a semiautomatic method for converting EXPRESS schemas into OWL ontologies and showed how Semantic Web Rule Language (SWRL) rules can be exploited to enrich an OWL version of IFC and create a semantic checking environment. To enable the encoding of semantics with the data, technologies such as Web Ontology Language are used to formally represent metadata. Ontology can describe concepts, relationships between entities, and knowledge representation [89]. These embedded semantics offer significant advantages such as reasoning over data and operating with heterogeneous data sources. Compared with the IFC used for BIM data models, ontology-based approach has a number of advantages:(1) ontology enables linking other domain data (such as sustainability) into the building information model; (2) ontology provides a formal and consistent taxonomy and classification structure to map concepts between domains; and (3) ontology can provide reasoning function for automated information processing and decision support by adopting semantic rules [90].

Currently, several studies have attempted to combine BIM and ontology for performing analyses, such as facility management [86], plan verification [91], precast components [92], construction cost estimation [93, 94], and sustainable design [95, 96]. As a result, it is expected that the use of ontology for integration of sustainability with BIM models will extend the interoperability of BIM and thus facilitate the sustainable structural design in the future.

Apart from the semantic web technologies, artificial intelligence (AI) has attracted great interest due to the capability of learning how to perform a specific task from known data. Many of the AI branches, such as machine learning, pattern recognition, neural networks, fuzzy logic, evolutionary computation, deep learning, expert systems, probability theory, discriminant analysis, swarm optimization, metaheuristic optimization, and decision trees, have been used in structural engineering. Among the different AI techniques, machine learning (ML), pattern recognition (PR), and deep learning (DL) have acquired considerable attention and are establishing themselves as a new class of intelligent methods for use in structural engineering [97]. AI techniques can be effectively used to check the general validity of laboratory and help minimize time-consuming laboratory or field tests. However, the application of AI techniques in the sustainable design remains to be developed. Recently, effort has been made [98] to combine BIM, data mining (knowledge discovery), and semantic technique to enable BIM-based information retrieval in support of evidence-based sustainable design in the early design phase. The proposed approach was based on the data and knowledge discovered in previous projects to enhance decision-making with the case-based design. The knowledge and data repository consists of 531 building models, while data mining was performed over the sensor data using motif discovery and association rule mining. It is a pioneer work that decision-making is based on knowledge discovery in previous projects and embedded in digital data by combining data mining and semantic modelling for case-based sustainable design. This approach highlights the potential benefits of using AI technology on the sustainable structural design in the future. A recent study conducted by Hao et al. [99] applied 3D graphic statics within a neural network model to facilitate the structural geometric form selection, which provides a more flexible method for the mutiobjective assessment of the solution space and thus enables designers to obtain different recommended solutions. In the future, it is evident that there is a tendency for designers to combine more advanced technology such as AI and semantic web to facilitate the repetitive and creative work and thus provide more solutions to advise designers in support of sustainable structural design.

The challenges that outside structural engineers face include that there is a need for architects to have effective corporation with structural engineers. The ultimate goals of sustainable design can be achieved by efficient information exchange and effective collaboration between structural engineers and architects. A central repository, namely, common data environment, would contribute to the high level of cooperation. In this case, there is a need to have a unified platform that can integrate sustainability considerations within a common environment between designers. The emerging technology, such as semantic web, knowledge graph, and even artificial intelligence, offers the greatest opportunities to achieve sustainable structural design. The fast-growing ontology technology can represent domain knowledge, entities, and their relationships in a variety of ways. Ontology not only enables cross-database search and database interoperability but also provides the means to represent any data formats, including unstructured, semi-structured, or structured data, enabling automated reasoning about data. Furthermore, in terms of the participant of a project, the clients should realize the importance of a structural engineer for a sustainable building and should have effective communication with structural engineers. The future legislation and organization also need to offer incentives to motivate structural engineers to consider the environmental performance of structural design.

5. Conclusions

Amidst the extensive scrutiny worldwide, environmental structural engineers have recently started to contemplate the influence of their outlines in terms of searching for efficient methods of reviewing energy and mechanisms for casting judgements which could compensate for the environmental downsides of their design resolutions. This significantly alters the outlook of the design industry in establishing building structures as the difficulty with measuring the impact of environmental energy is not simple, particularly when considering the sustainability factors impacting on the building.

This paper presents a state-of-the-art review of sustainable design from all the standards, databases, and tools regarding sustainability in the building design domain for the current practice of sustainable structural design. An extensive modern insight into sustainable structural design, including strategies and indicators, as well as BIM-enabled methodology, is also presented. The contribution from structural engineers in striving for resolute and sustainable objectives is now known, particularly in terms of the advancement of processes to fulfil these aims. Furthermore, the notion of sustainability in connection to structural design has gradually obtained a more comprehensive sentiment, incorporating environmental, social, and financial factors over the process. Regardless of a great deal of efforts made towards streamlining the LCA process, the highly fragmented knowledge and the way of working within the building domain increase the difficulty of the multiobjective structural design (i.e., safety, cost, and environmental impact). There is always a priority or tradeoff among these factors. How to balance these parameters remains a challenge. A systematic approach (multiobjective) beginning with the standardised calculation procedure for SSD is essential for practitioners to achieve a sustainable structure and building.

The challenge for achieving a sustainable structure is multiple: from centralisation of different domain knowledge in a common environment to an explicit process that enables efficient and systematic information exchange between designers. The authors anticipate the forthcoming AI and semantic technology together with open BIM as a chance for achieving a holistic sustainable design in the future.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to acknowledge the financial support provided by the Educational Department of Liaoning Province (Grant nos. JDL2019036 and JDL 2019018) and the Department of Science and Technology of Liaoning Province (Grant no. 2019-BS-041).

References

[1] AIJ and IBEC, Architecture for a Sustainable Future, *All about the Holistic Approach in Japan*, Institute for Building Environment and Energy Conservation, Tokyo, Japan, 2005.

[2] United Nations Environment Program Sustainalbe Buildings and Climate Initiative, *Buildings and Climate Change. Summary for Decision-Makers*, United Nations Environment Program Sustainalbe Buildings and Climate Initiative, Paris, France, 2009.

[3] J. McLennan, *The Philosophy of Sustainable Design: The Future of Architecture*, Ecotone Publishing, Topeka, KS, USA, 2004.

[4] K. Tsimplokoukou, M. Lamperti, and P. Negro, *Building Design for Safety and Sustainability*, Joint Research Centre, European Union, Brussels, Belgium, 2014.

[5] ISO/TC207/SC5, *Life Cycle Assessment*, International Organization for Standardizaion, Geneva, Switzerland, 1993.

[6] ISO/TC59/SC17, *Sustainability in Buildings and Civil Engineering Works*, International organization for Standardization, Geneva, Switzerland, 2002.
[7] CEN/TC350, *Sustainability of Construction Works*, European Committee for Standardization, Brussels, Belgium, 2004.
[8] Coldstream Consulting, *LCA Protocol for Clean Environment Commission Keeyask Proceedings*, Coldstream Consulting Ltd., Vancouver, Canada, 2013.
[9] G. Hammond and C. Jones, *Inventory of Carbon and Energy (ICE)*, University of Bath, Bath, UK, 2010.
[10] C. D. Wolf, F. Pomponi, and A. Moncaster, "Measuring embodied carbon dioxide equivanlent of buildings: a review and critique of current industry practice," *Energy and Buildings*, vol. 140, pp. 68–80, 2017.
[11] C. Say and A. Wood, "Sustainable rating systems around the world," *CTBUH*, vol. 2, pp. 18–29, 2008.
[12] S. G. Al-Ghamdi and M. M. Biles, "Green building rating systems and whole-building life cycle assessment: comparative study of the existing assessment tools," *Journal of Architectural Engineering*, vol. 23, no. 1, pp. 1–9, 2017.
[13] F. Jalaei and A. Jrade, "Integrating building information modelling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings," *Journal of Information Technology in Construction*, vol. 19, pp. 494–519, 2014.
[14] J. Basbagill, F. Flager, M. Lepech, and M. Fischer, "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts," *Building and Environment*, vol. 60, pp. 81–92, 2013.
[15] A. Oti and J. Tah, *Disitizing the Assessment of Embodied Energy and Carbon Footprint of Buildings Using Emerging Building Information*, CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, 2015.
[16] H.-L. Chi, X. Wang, and Y. Jiao, "BIM-enabled structural design: impacts and future developments in structural modelling, analysis and optimisation," *Archives of Computational Methods in Engineering*, vol. 22, no. 1, pp. 135–151, 2015.
[17] M. A. Zanni, R. Soetanto, and K. Ruikar, "Towards a BIM-enabled sustainable building design process: roles, responsibilities, and requirements," *Architectural Engineering and Design Management*, vol. 13, no. 2, pp. 101–129, 2017.
[18] N. Wang and H. Adeli, "Sustainable building design," *Journal of Civil Engineering and Management*, vol. 20, no. 1, pp. 1–10, 2014.
[19] D. Miller, J.-H. Doh, K. Panuwatwanich, and N. van Oers, "The contribution of structural design to green building rating systems: an industry perspective and cpmparison of life cycle energy considerations," *Sustainable Cities and Society*, vol. 16, pp. 39–48, 2015.
[20] S. Kaethner and J. Burrideg, "Embodied CO_2 of structural frames," *The Structural Engineer*, vol. 90, no. 5, pp. 33–40, 2012.
[21] M. D. Webster, "Relevance of structural engineers to sustainable design of buildings," *Structural Engineering International*, vol. 14, no. 3, pp. 181–185, 2004.
[22] D. Wood, "The structural engineer and sustainable design," 2015, http://www.douglaswood.biz/greenbulletin.pdf.
[23] S. Hou, H. Li, and Y. Rezgui, "Ontology-based approach for structural design considering low embodied energy and carbon," *Energy and Buildings*, vol. 102, pp. 75–90, 2015.
[24] M. Pongiglione and C. Calderini, "Sustainable structural design: comprehensive literature review," *Journal of Structure Engineering*, vol. 142, pp. 1–15, 2016.
[25] J. E. Anderson and R. Silman, "A life cycle inventory of structural engineering design strategies for greenhouse gas reduction," *Structural Engineering International*, vol. 19, no. 3, pp. 283–288, 2009.
[26] J. M. Danatzko and H. Sezen, "Sustainable structural design methodologies," *Practice Periodical on Structural Design and Construction*, vol. 16, no. 4, pp. 186–190, 2011.
[27] R. Sinha, M. Lennartsson, and B. Frostell, "Environmental footprint assessment of building structure: a comparitive study," *Building and Environment*, vol. 104, pp. 162–171, 2016.
[28] A. A. Guggemos and A. Horvath, "Comparison of environmental effects of steel- and concrete-framed buildings," *Journal of Infrastructure Systems*, vol. 11, no. 2, pp. 93–101, 2005.
[29] D. W. Catherine, F. Yang, C. Duncan, and A. Charlson, "Material quantities and embodied carbon dioxide in structures," *Engineering Sustainability*, vol. 169, no. 4, pp. 150–161, 2015.
[30] Y.-B. Jung and K.-H. Yang, "Low CO_2 design approach of reinforced concrete structures for the targeted CO_2 reduction," *Journal of Structural Integrity and Maintenance*, vol. 1, no. 2, pp. 81–87, 2016.
[31] D. Miller and J. H. Doh, "Incorporating sustainable development principles into building design: a review from a structural perspective including case study," *Struct. Design Tall Spec. Build*, vol. 24, no. 6, pp. 412–439, 2015.
[32] M. Borchers, "Importance of structural engineering in sustainable and low carbon design," *The Structural Engineer*, vol. 88, no. 9, pp. 14–16, 2010.
[33] M. Chaudhary and A. Piracha, "Examining the role of structural engineers in green building ratings and sustainable development," *Australian Journal of Structural Engineering*, vol. 14, no. 3, pp. 217–227, 2013.
[34] E. S. Bakhoum and D. C. Brown, "Developed sustainable scoring system for structural materials evaluation," *Journal of Construction Engineering and Management*, vol. 138, no. 1, pp. 110–119, 2012.
[35] D. M. Kestner, *Sustainability Guidelines for the Structural Enginner*, ASCE, Reston, VA, USA, 2010.
[36] M. D. Webster, *"The Relevance of Structural Engineers to Green Building Design," in Structures Congress*, ASCE, Reston, VA, USA, 2005.
[37] C. D. Wolf, O. Iuorio, and J. Ochsendorf, "Structural material quantities and embodied carbon coefficients: challenges and opportunities," in *Proceedings of the Sustainable Structures Symposium*, Portland State University, Portland, OR, USA, April 2014.
[38] A. H. Oti, W. Tizani, F. H. Abanda, A. Jaly-Zada, and J. H. M. Tah, "Structural sustainability appraisal in BIM," *Automation in Construction*, vol. 69, pp. 44–58, 2016.
[39] G. Aouad, A. Lee, and S. Wu, *Constructing the Future: ND Modelling*, Taylor & Francis Group, Milton, UK, 2006.
[40] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons, Hoboken, NJ, USA, 2nd edition, 2011.
[41] H.-Y. Chong and X. Wang, "The outlook of building information modeling for sustainable development," *Clean Technologies and Environmental Policy*, vol. 18, no. 6, pp. 1877–1887, 2016.
[42] N. O. Nawari and M. Sgambelluri, "The role of national BIM standard in structural design," in *Proceedings of the 2010 Structures Congress*, ASCE, Orlando, FL, USA, May 2010.

[43] F. H. Abanda, C. Vidalakis, A. H. Oti, and J. H. M. Tah, "A critical analysis of building information modelling systems used in construction projects," *Advances in Engineering Software*, vol. 90, pp. 183–201, 2015.
[44] S. Eleftheriadis, D. Mumovic, and P. Greening, "Life cycle energy efficiency in building structures: a review of current developments and future outlooks based on BIM capabilities," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 811–825, 2017.
[45] B. Ilhan and H. Yaman, "Green building assement tool (GBAT) for integrated BIM-based design decisions," *Automation in Construction*, vol. 70, pp. 26–37, 2016.
[46] F. Shadram, T. D. Johansson, W. Lu, J. Schade, and T. Olofsson, "An integrated BIM-based framework for minimizing embodied energy during building design," *Energy and Buildings*, vol. 128, pp. 592–604, 2016.
[47] A. Stadel, J. Eboli, A. Ryberg, J. Mitchell, and S. Spatari, "Intelligent sustainable design: integration of carbon accounting and building information modeling," *Journal of Professional Issues in Engineering Education and Practice*, vol. 137, no. 2, pp. 51–54, 2011.
[48] H.-Y. Chong, C.-Y. Lee, and X. Wang, "A mixed review of the adoption of building information modelling (BIM) for sustainability," *Journal of Cleaner Production*, vol. 142, pp. 4114–4126, 2017.
[49] Y. Schwartz, S. Eleftheriadis, R. Raslan, and D. Mumovis, "Semantically enriched BIM life cycle assessment to enhance buildings' environmental performance," in *Proceedings of the CIBSE Technical Symposium*, Edinburgh, UK, 2016.
[50] F. Consoli, *Guidelines for Life-Cycle Assessment: A Code of Practice*, Society of Environmental Toxicology and Chemistry, Sesimbra, Portugal, 1993.
[51] J. B. Guinée, R. Heijungs, G. Huppes, and A. Zamagni, "Life cycle assessment: past, present, and future," *Environmental Science & Technology*, vol. 45, no. 1, pp. 90–96, 2011.
[52] M. C. McManus and C. M. Taylo, ""The changing nature of life cycle assessment," biomass and [62] ELCD, European reference life cycle database," 2016, http://eplca.jrc.ec.europa.eu/ELCD3/.
[53] US LCI Database, "National renewerbale energy laboratory," 2017, http://www.nrel.gov/lci/.
[54] Ecoinvent, 2017, http://www.ecoinvent.org/.
[55] "GaBi database," *Bioenergy*, vol. 82, pp. 13–26, 2015, http://www.gabi-software.com/international/databases/gabi-databases/.
[56] Athena, Athena Sustainable Material Institute, 2017, http://www.athenasmi.org/our-software-data/lca-databases/.
[57] A. M. Moncaster and J.-Y. Song, "A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings," *International Journal of Sustainable Building Technology and Urban Development*, vol. 3, no. 1, pp. 26–36, 2012.
[58] A. Haapio and P. Viitaniemi, "A critical review of building environmental assessment tools," *Environmental Impact Assessment Review*, vol. 28, no. 7, pp. 469–482, 2008.
[59] O. Ortiz, F. Castells, and G. Sonnemann, "Sustainability in the construction industry: a review of recent developments based on LCA," *Construction and Building Materials*, vol. 23, no. 1, pp. 28–39, 2009.
[60] M. Erlandsson and M. Borg, "Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs," *Building and Environment*, vol. 38, no. 7, pp. 919–938, 2003.
[61] BREEAM, Building Research Establishment (BRE) Group, 2017, http://www.breeam.com/.
[62] LEED, US Green Building Council, 2017, http://www.usgbc.org/leed.
[63] Green Star rating system, Green Building Council Australia, 2017, http://gbca.org.au/green-star/rating-system/.
[64] CASBEE, *Comprehensive Assessment System for Built Environment Efficiency (CASBEE)*, Japan Sustainable Building Consortium (JSBC) and Institute for Building Environment and Energy Conservation (IBEC), Baton Rouge, LA, USA, 2017, http://www.ibec.or.jp/CASBEE/english/.
[65] DGNB, German Sustainable Building Council, 2017, http://www.dgnb.de/en/.
[66] D. M. Frangopol, K.-Y. Lin, and A. C. Estes, "Life-cycle cost design of deteriorating structures," *Journal of Structural Engineering*, vol. 123, no. 10, pp. 1390–1401, 1997.
[67] R. J. Cole and P. C. Kernan, "Life-cycle energy use in office buildings," *Building and Environment*, vol. 31, no. 4, pp. 307–317, 1996.
[68] P. Hájek, C. Fiala, and M. Kynclova, "Life cycle assessments of concrete structures—a step towards environmental savings," *Structural Concrete*, vol. 12, no. 1, pp. 13–22, 2011.
[69] D. Yeo and R. D. Gabbai, "Sustainable design of reinforced concrete structures through embodied energy optimization," *Energy and Buildings*, vol. 43, no. 8, pp. 2028–2033, 2011.
[70] D. Yeo and F. A. Potra, "Sustainable design of reinforced concrete structures through CO_2 emission optimization," *Journal of Structural Engineering*, vol. 141, no. 3, 2015.
[71] P. Foraboschi, M. Mercanzin, and D. Trabucco, "Sustainable structural design of tall buildings based on embodied energy," *Energy and Buildings*, vol. 68, pp. 254–269, 2014.
[72] V. J. L. Gan, C. L. Wong, K. T. Tse, and J. C. P. Cheng, "Parametric modelling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings," *Advanced Engineering Informatics*, vol. 42, pp. 100962.1–100962.16, 2019.
[73] A. U. Weerasuriya, X. Zhang, V. J. L. Gan, and Y. Tan, "A holistic framework to utilize natural ventilation to optimize energy performance of residential high-rise buildings," *Building and Environment*, vol. 153, pp. 218–232, 2019.
[74] S. Hou, *An ontology-based holistic approach for multi-objective sustainable structural design*, Ph.D. thesis, Cardiff University, Cardiff, UK, 2015.
[75] K. S. Moon, "Sustainable structural engineering strategies for tall buildings," *The Structural Design of Tall and Special Buildings*, vol. 17, no. 5, pp. 895–914, 2008.
[76] S. Eleftheriadis, D. Mumovic, P. Greening, and A. Chronis, "BIM enabled optimisation framework for environmentally responsible and structurally efficient design systems," in *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining*, Oulu, Finland, 2015.
[77] F. Abanda, A. Oti, and J. Tah, "Digitizing the assessment of embodied energy and carbon footprint of buildings using emerging building information modeling," in *The Carbon Footprint Handbook*, pp. 303–330, CRC Press, Boca Raton, FL, USA, 2015.
[78] S. Liu, X. Meng, and C. Tam, "Building information modeling based building design optimization for sustainability," *Energy and Buildings*, vol. 105, pp. 139–153, 2015.
[79] D. M. Kestner, J. Goupil, and E. Lorenz, *Sustainability Guidelines for the Structural Engineer*, ASCE, Reston, VA, USA, 2010.
[80] R. Brahme, A. Mahdavi, K. P. Lam, and S. Gupta, ""Complex building performance analysis in the early stages of design," in

Proceedings of the Seventh International IBPSA Conference, pp. 661–668, IBPSA, Rio de Janeiro, Brazil, August 2001.

[81] A. H. Oti and W. Tizani, “BIM extension for the sustainability appraisal of conceptual steel design,” *Advanced Engineering Informatics*, vol. 29, no. 1, pp. 28–46, 2015.

[82] J. Beetz, J. Van Leeuwen, and B. De Vries, “IfcOWL: a case of transforming express schemas into ontologies,” *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol. 23, no. 1, pp. 89–101, 2009.

[83] S. Krima, R. Barbau, X. Fiorentine, R. Sudarsan, and R. Sriram, *OntoSTEP: OWL-DL Ontology for STEP*, National Institute of Standards and Technology, NISTIR, Gaithersburg, MA, USA, 2009.

[84] R. Barabu, S. Krima, S. Rachuri, and A. Narayanan, “OntoSTEP: enriching product model data using ontologies,” *Computer-Aided Design*, vol. 44, no. 6, pp. 575–590, 2012.

[85] H. Schevers and R. Drogemuller, “Converting the industry foundation classes to the web ontology language,” in *Proceedings of the First International Conference on, Semantics, Knowledge and Grid, SKG 05*, IEEE, Beijing, China, November 2005, http://www.ieeeplore.ieee.org/xpl/articleDetails.jsp?arnumber=4125861.

[86] C. Mignard and C. Nicolle, “Merging BIM and GIS using ontologies application to urban facility management in ACTIVe3D,” *Computers in Industry*, vol. 65, no. 9, pp. 1276–1290, 2014.

[87] H. Knublauch, R. W. Fergerson, N. F. Noy, and M. A. Musen, “The Protégé OWL plugin: an open development environment for semantic web applications,” in *The Senmantic Web-ISWC 2004*Springer, Berlin, Germany, 2004.

[88] P. Pauwels and W. Terkaj, “EXPRESS to OWL for construction industry: towards a recommendable and usable ifcOWL ontology,” *Automation in Construction*, vol. 63, pp. 100–133, 2016.

[89] H. M. T. Joseph and F. A. Henry, “Sustainable building technology knowledge representation: using Semantic Web techniques,” *Advanced Engineering Informatics*, vol. 25, pp. 547–558, 2011.

[90] E. P. Karan and J. Irizarry, “Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services,” *Automation in Construction*, vol. 53, pp. 1–12, 2015.

[91] B. T. Zhong, L. Y. Ding, P. E. D. Love, and H. B. Luo, “An ontological approach for technical plan definition and verification in construction,” *Automation in Construction*, vol. 55, pp. 47–57, 2015.

[92] G. Costa and L. Madrazo, “Connecting building component catalogues with BIM models using semantic technologies: an application for precast concrete components,” *Automation in Construction*, vol. 57, pp. 239–248, 2015.

[93] S.-K. Lee, K.-R. Kim, and J.-H. Yu, “BIM and ontology-based approach for building cost estimation,” *Automation in Construction*, vol. 41, pp. 96–105, 2014.

[94] Z. Ma and Z. Liu, “Ontology-and freeware-based platform for rapid development of BIM applications with reasoning support,” *Automation in Construction*, vol. 90, pp. 1–8, 2018.

[95] M. Niknam and S. Karshenas, “Sustainable design of building using semantic BIM and semantic web services,” *Procedia Engineering*, vol. 118, pp. 909–917, 2015.

[96] J. Zhang, H. Li, Y. Zhao, and G. Ren, “An ontology-based approach supporting holistic structural design with the consideration of safety, environmental impact and cost,” *Advances in Engineering Software*, vol. 115, pp. 26–39, 2018.

[97] H. Salehi and R. Burgueño, “Emerging artificial intelligence methods in structural engineering,” *Engineering Structures*, vol. 171, pp. 170–189, 2018.

[98] E. Petrova, P. Pauwels, K. Svidt, and R. L. Jensen, “From patterns to evidence: enhancing sustainable building design with pattern recognition and information retrieval approaches,” in *Proceedings of the 12th European Conference on Product and Process Modelling*, ECPPM, Copenhagen, Denmark, September 2018.

[99] Z. Hao, V. Moosavi, and M. Akbarzadeh, “Machine learning assisted evaluations in structural design and construction,” *Automation in Construction*, vol. 119, pp. 1033–1046, 2020.