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Review

Potential Integration of Bridge Information Modeling and Life Cycle Assessment/Life Cycle Costing Tools for Infrastructure Projects within Construction 4.0: A Review

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Abstract: Construction 4.0 is a platform that combines digital and physical technologies to enhance the design and construction of the built environment. Bridge Information Modeling (BrIM), a component of Construction 4.0′s digital technologies, streamlines construction processes and promotes collaboration among project stakeholders. In this study, a comprehensive literature review and bibliometric and content analysis are conducted on building information modeling (BIM), life cycle assessment (LCA), life cycle cost (LCC), BrIM, and Bridge LCA. This study investigates the potential integration of BrIM, LCA, and LCC as inputs for bridges' LCA to enhance decision making by providing designers with detailed and interactive cost and environmental information throughout an asset's lifecycle and explores the functionalities of Construction 4.0 and its potential influence on the economy and sustainability of bridge projects. The reviewed literature showed that the tools currently used to apply LCA and LCC methods for infrastructure assets lack the ability to identify possible integration with BrIM and hold limitations in their key functions for identifying the utmost features that need to be adopted in the creation of any tool to increase the general resilience of bridges and infrastructure.

Keywords: construction 4.0; bridge information modeling (BrIM); life cycle assessment (LCA); life cycle cost (LCC); building information modeling (BIM)

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1. Introduction

Industry 4.0 is known as the fourth industrial revolution, an idea that specifically refers to producing and manufacturing via digital change and new technologies [1]. While Construction 4.0 was adapted from Industry 4.0, it is a new vision for the Architecture, Engineering, and Construction (AEC) industry [2]. Several aspects should be considered to improve the transformation to a new area, like cross-organizational networks and relevant technologies used at all steps [3]. For the construction and manufacturing industries, advanced technologies could enhance products' configurations to ensure they fulfill customers' needs. Therefore, additional studies are crucial to improve the knowledge and determine the advantages of applying new technologies and the aspects that are needed to evaluate and use them [4]. The shift from Industry 3.0 to 4.0 provided additional access to information technologies that permit automatic processes [5]. It is vital to have adequate information and a more accurate understanding of the relevant mechanisms and their capacity to succeed in the integration process [6]. Coupling new and existing tools requires an effective network so as to enable the exchange of information between organizations, facilitate the cross-organizational connection of technologies, and allow for these operations during the whole process [1].

Construction 4.0 articulates changes needed in the AEC industry by considering the concepts of Industry 4.0. Adopting the concept of Building Information Modeling (BIM) shifted the AEC industry toward digitizing analog information like building plans [6]. Information technologies coupled with automated construction methods are crucial for optimizing the selection of construction materials, building configurations, and improved performance. The AEC industry has several sections and processes that are often consecutive [7], making it difficult to use digital technologies needed for the flow of information and data exchange [8]. Nevertheless, studies that tackle the aspects of data processing and management are few when compared to the investigated technologies. Therefore, proper strategies are required, at the organizational and industrial levels, to apply an efficient framework for the transition in adopting the development of Construction 4.0. Some studies have revealed that using technology as a tool to evolve construction processes is useful. For instance, BIM can be the main element in changing the entire construction industry of designing and constructing buildings, much like BrIM would be for bridges. Construction projects can be controlled directly in a digital environment using integrated platforms, like 4D planning, 5D cost estimation, and clash detection [9]. A newer construction industry needs more intelligent resources, but intelligent construction is still in its first stages [10]. Moving toward a digital environment is an essential strategy with which to change the construction industry by improving its performance and efficiency [11]. Notably, the rate of production in the manufacturing sector has been higher compared to that of other industries, particularly when placed in contrast with the construction industry. Despite the efforts employed in developing processes for industrializing the construction industry, it is still considered to be part of the manufacturing industry [12].

Construction 4.0 is a new approach used to apply and understand construction processes, leading to better productivity and innovation [13,14]. For instance, autonomous systems, additive manufacturing, big data, robotics, augmented reality, and IoT are parts of the primary pillars of Construction 4.0. Another new technology that the construction sector needs to adopt is cyber security. At present, there are few applications used by the construction industry, including BIM, BrIM, modularization, and 3D printing; therefore, the construction industry should adopt and use the concepts of Industry 4.0 [15]. In this regard, it should be noted that adopting Construction 4.0 can significantly and positively influence the management of sustainable infrastructure.

Bridge Information Modeling (BrIM) is a new concept originating from BIM with a focus on bridge projects. Like BIM, BrIM was introduced to efficiently manage the exchange of information between stakeholders concerning bridge structures. BrIM applications have been proposed to combine information from the architecture, engineering, construction, and operation sectors [16]. Since BIM has demonstrated efficient results in integrating buildings' data to control their design, construction, and performance over their anticipated life cycles, it is anticipated that BrIM can greatly assist in offering proper design alternatives for the construction, maintenance, and rehabilitation of bridges. BrIM permits designers to animate the geometry of bridges during the design stage through the creation of smart virtual 3D models, which include all the information and data concerning bridges' components [17], and by using its features to evaluate the inspection data of bridges and present a method for monitoring their structural conditions. BrIM could be used over the entire life cycles of bridges by automating and combining the processes of their design, construction, maintenance, and operation. Shim et al. [18] presented a 3D BrIM model for the design and construction of bridge projects. They enhanced bridge life cycle management via a BrIM platform, which led to encouraging outcomes at its conceptual design stage and detected clashes during its construction phase. Moreover, Elbeltagi and Dawood [19] proposed a computer-based model to help visualize the construction process of repetitive projects over time and control their cost information within a BrIM environment. Lee et al. [20] assessed the capabilities of 3D BrIM models during the design and construction of concrete box-girder bridges and presented a new life cycle management system to unify the design and construction of major parts for this type of project.

Ding et al. [21] revealed that a computer model could be used to convert a 3D CAD model into multidimensional models by using a framework that simplifies the exchange of information between project participants and helps them with their decision making. Jeong et al. [22] introduced a simulation model to examine variations in productivity rates by extracting necessary data and automatically estimating the variability in the production process used to generate schedules for construction activities of a dynamic nature.

After navigating through the above-listed studies, one could conclude that the concepts of BrIM can be used as an efficient integration approach to merge various applications. Moreover, BrIM has simplified compatibility and interoperability with other applications and can improve projects' durations and cost with less error-prone outcomes. Various tools are currently used to apply the concepts of BrIM. Some of these tools focus only on the geometry of bridges by covering the architectural components, while others concentrate on the structural sections of a bridge by looking at its structural elements and their resistance; however, all these tools are used by the construction industry to control and reduce engineers' activities and tasks. Several types of software are used for structural analysis (e.g., Bridge CSI and Tekla structures) and for visualizations in a 3D environment (e.g., Autodesk Civil 3D-CAD and Revit). BrIM tools can be utilized over the whole life cycle of bridges. Using these tools at the conceptual design stage would reduce future conflicts and help in detailing and executing additional analyses. These tools appear to be beneficial and could lead to promising outcomes. However, existing challenges can influence the use of BrIM tools, whose main purpose is to exchange data. Therefore, BrIM tools must (1) be able to provide all the necessary specifications and quantities; (2) be able to provide proper visualization of the proposed bridge to effectively evaluate potential alternatives; and (3) be able to reduce any adjustments and modifications made during the detailed design stage.

2. Materials and Methods

This study uses a bibliometric analysis to search for examples of the interdisciplinary integration of Construction 4.0, BIM, LCA, LCC, BrIM, sustainable infrastructure projects, and climate change by examining the volume of pertinent literature from the past 20 years and the uncertainty surrounding the future directions and trends of this field of research. This bibliometric analysis contains a quantitative examination of the data from the documents in the literature, including the year, sources, keywords, research themes, research directions, research methodologies, application domains, and emerging trends. The research method employed in this study was adapted from the work of Chen et al. and Teng et al. [23,24]. It minimizes the writers' subjective judgments and produces clear-cut and objective results [25].

Using the Web of Science Core Collection (WoSCC) to locate pertinent articles for a quantitative analysis of the literature and then importing them into the VOSviewer 1.6.18 software to display keywords is an efficient method to adopt. One of the most reliable databases for indexing scientific citations is the Web of Science (WoS) [26]. Hence, we used VOSviewer 1.6.18 software to help us attain a thorough understanding of the existing situation and upcoming growth in the research hotspots in the areas of Construction 4.0, Industry 4.0, BIM, LCA, LCC, BrIM, sustainable infrastructure projects, and climate change. To achieve the goals of this study, a simplified methodology that consists of eight steps was realized, as shown in Figure 1.

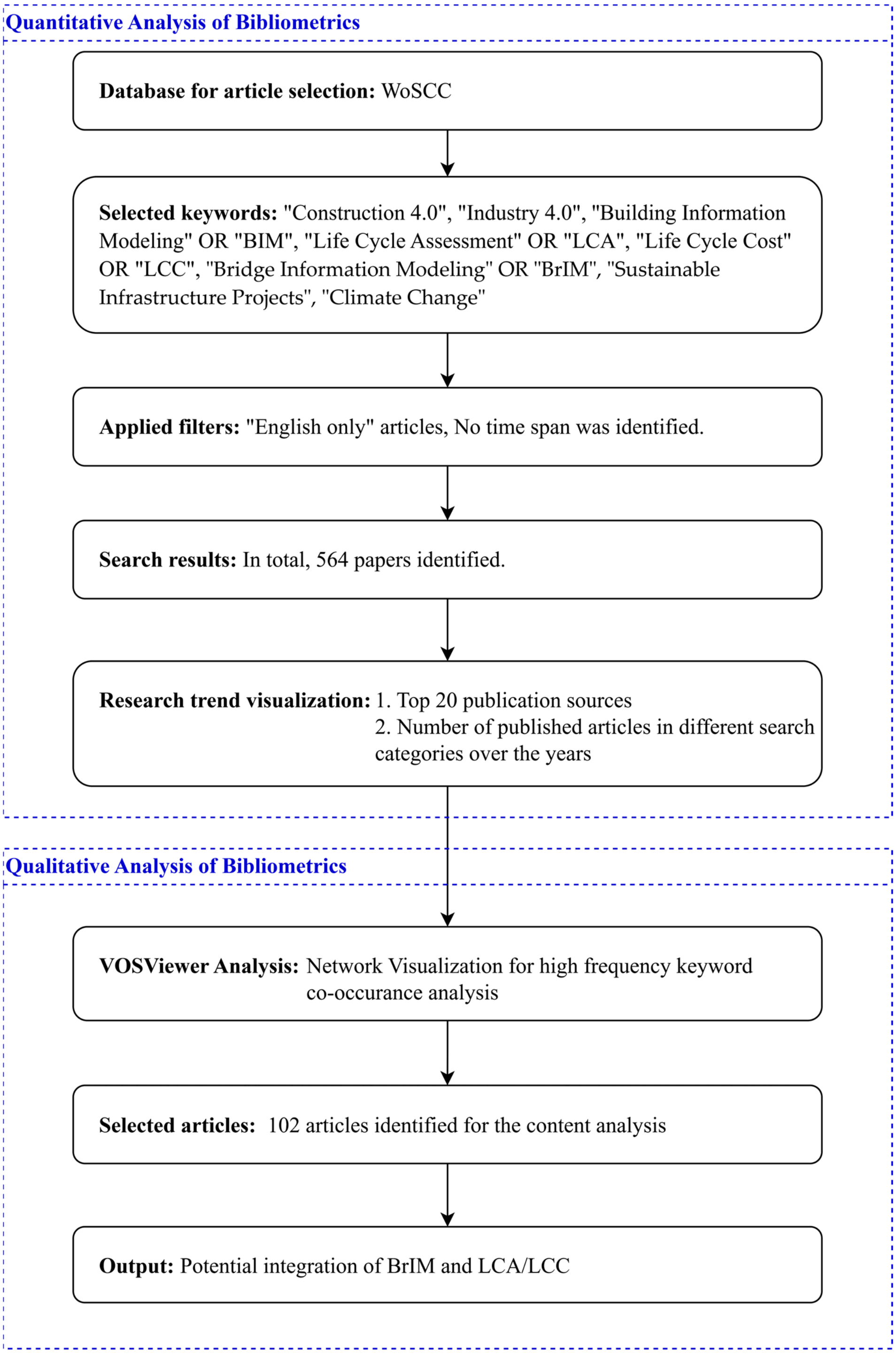

Figure 1. Research methodology's Steps.

2.1. Data Collection and Bibliometric Analysis

In this study, the database of WoSCC was the main source of the collected data, while the following keywords were used to find the most pertinent studies: Construction 4.0, Industry 4.0, BIM, LCA, LCC, BrIM, sustainable infrastructure projects, and climate change. The keywords' abbreviations were accompanied with their full forms in the search steps, and the flexible use of Boolean operators like "AND" or "OR" was also applied. The results of the collected data are organized in Table 1. Initially, 564 preliminary results were collected, and then a filtering process aligned with this study's objectives was applied. First filtering was conducted according to article titles, abstracts, and keywords to identify the papers that were pertinent to this study. Then, they were examined and organized in a spreadsheet by year, location, research objective, research methodology, and research type for analysis. Second filtering concerned the effectiveness of the proposed solutions for the integration of the mentioned areas that were assessed in the articles, which led to us retaining 102 articles, categorized into 3 tables, for a detailed content analysis (refer to the Supplementary Information [17,27–86]).

Table 1. Results of the collected data for the most relevant literature retrieved from the database of WoSCC.

Web of Science Core Collection	SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH, CCR-EXPANDED, IC	No. of Results
Search steps	#1 = ("building information modeling" or "BIM") (Topic) and ("climate resiliency" or "climate resilience")	2
	#2 = ("construction 4.0" OR "industry 4.0") AND ("infrastructure projects" OR "sustainable infrastructure")	5
	#3 = ("construction 4.0" OR "industry 4.0") AND ("building information modeling" OR "BIM")	118
	#4 = ("building information modeling" OR "BIM") AND ("life cycle assessment" OR "LCA")	329
	#5 = ("building information modeling" OR "BIM") AND ("life cycle cost" OR "LCC")	114
	#6 = ("building information modeling" OR "BIM") AND ("life cycle assessment" OR "LCA") AND ("life cycle cost" OR "LCC")	28
	#7 = ("bridge information modeling" OR "BrIM")	43
	#8 = ("bridge information modeling" OR "BrIM") AND ("construction 4.0" OR "industry 4.0")	1
	#9 = ("bridge information modeling" OR "BrIM") AND ("life cycle assessment" OR "LCA")	0
	#10 = ("bridge information modeling" OR "BrIM") AND ("life cycle cost" OR "LCC")	0
	#11 = #8 OR #7 OR #6 OR #5 OR #4 OR #3 OR #2 OR #1	564
Qualified Records	102	
Timespan	2003–2022	

Table 1 clearly indicates that using BrIM to integrate LCA and LCC for bridges is a nascent subject with no published records, while using BIM and LCA has been intensively explored, with a record of more than 300 publications. Table 2 lists the top 20 sources of the searched topics. As illustrated in Table 2, Sustainability is the most productive journal among the searched sources, with 63 articles, followed by the Journal of Cleaner Production, Buildings, and Automation in Construction, with 32, 26, and 24 articles, respectively. For a journal to be among the top 20 most effective sources, it must have at least five published articles related to the selected keywords.

The number of publications is the key indicator for determining the trends in scientific research. The growth over the time of published papers related to the chosen keywords is displayed in Figure 2. Papers related to BIM were first published in the year 2003, whereas the ones related to Construction 4.0, as well as the ones covered in this paper, were initially published in year 2016.

Table 2. Top 20 most productive sources regarding Construction 4.0, Industry 4.0, BIM, LCA, LCC, climate change, BrIM, and sustainable infrastructure projects.

Ranking	Source Titles (Journals)	No. of Publications
Top 1	Sustainability	63
Top 2	Journal of Cleaner Production	32
Top 3	Buildings	26
Top 4	Automation in Construction	24
Top 5	Journal of Building Engineering	21
Top 6	Iop Conference Series Earth and Environmental Science	20
Top 7	Building and Environment	16
Top 8	Energy and Buildings	16
Top 9	Sustainable Built Environment Conference	15
Top 10	International Journal of Construction Management	12
Top 11	Journal of Information Technology in Construction	11
Top 12	Procedia Engineering	10
Top 13	Applied Sciences Basel	8
Top 14	Life Cycle Analysis and Assessment in Civil Engineering Towards an Integrated Vision	8
Top 15	Sustainable Cities and Society	8
Top 16	Energies	7
Top 17	Construction Innovation England	6
Top 18	Smart and Sustainable Built Environment	6
Top 19	Advanced Engineering Informatics	5
Top 20	Built Environment Project and Asset Management	5

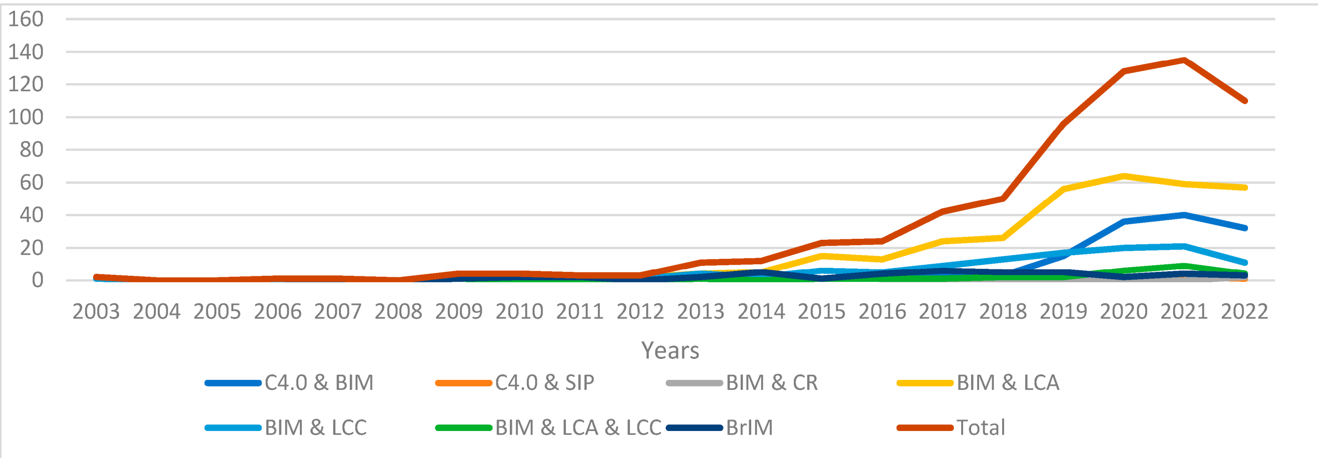

Figure 2. Number of papers published each year in the specified categories from the year 2003 to 2023 in the WoSCC database.

2.2. Network Visualization

In total, 563 papers were collected and exported as "Plain Text Files" with full records and cited references for analysis and imported into the VOSviewer network visualization software to perform a term co-occurrence analysis. Figure 3 displays the outcome, with 56 keywords organized into 6 distinct color clusters: red; green; dark blue; yellow; purple; and light blue.

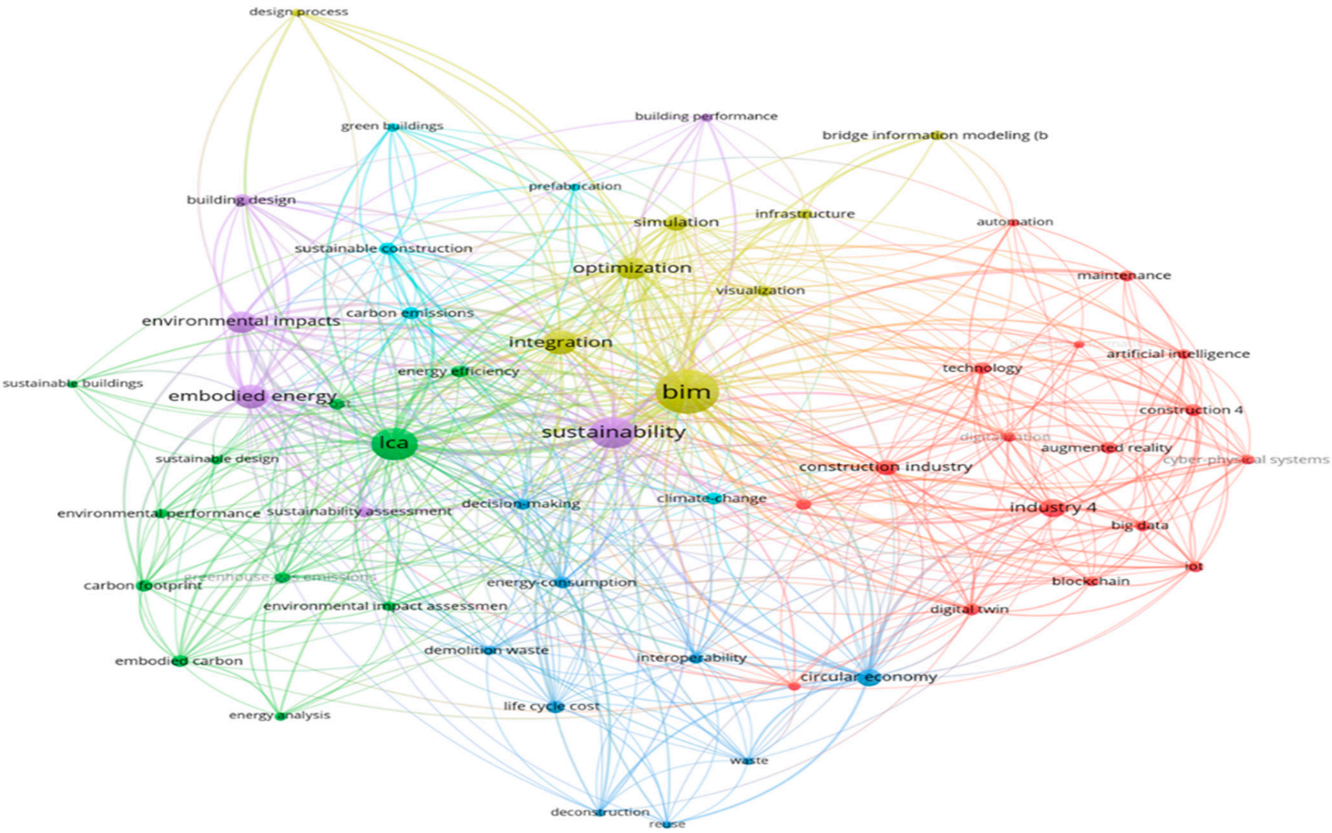

Figure 3. Keyword network visualization regarding Construction 4.0, Industry 4.0, BIM, LCA, LCC, Climate change, BrIM, and Sustainable Infrastructure Project.

The number of occurrences for each keyword is indicated by the size of the circular nodes. The frequency with which the same keyword appears in various articles increases with the node's size. The largest node is for the keyword BIM. The distance between two keywords indicates how closely they are related and similar, while a line's thickness shows the strength of their relation.

Looking at the above clusters, one may realize that three keywords, BIM, life cycle assessment (LCA), and sustainability, are highly associated with each other, and their appearance is frequent, which is why they are in the center of Figure 3. On the other hand, the keywords Construction 4.0 and Bridge Information Modeling (BrIM) have smaller nodes at the edge of the diagram are not closely related to each other, as shown in Figure 4. Therefore, the keyword network visualizations on the themes of Construction 4.0 and BrIM require additional investigation and analysis.

2.3. Countries Engagement Analysis

To describe the worldwide cooperative acts from a macroscopic perspective, a network of the authors' countries was created. A total of 25 nations out of 41 are listed based on a minimum of 5 publications, as shown in Table 3 and Figure 5, which present detailed information about the countries that have been active as per the total number of qualified studies. China and the USA top the list for the number of publications, which reveals that they have made a considerable contribution to this area. However, China has the highest link strength, which is a clear indication that it played an important role in the cooperation network and made significant contributions to the improvement of the research. Collectively, the EU countries in Table 3 have produced the most publications (200+), considering both their total population and geographical area. This indicates that Europe has advanced the topic greatly.

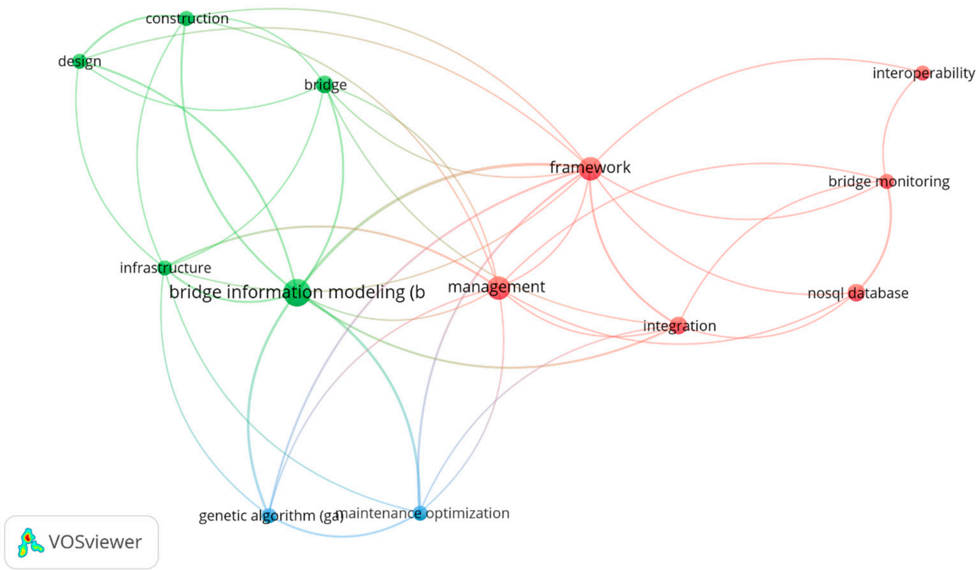

Figure 4. Keyword network visualization regarding BrIM.

Table 3. List of countries/regions with the highest link strength.

Country	Documents	Citations	Total Link Strength
Peoples R China	103	1933	914
Australia	62	1795	663
USA	77	1906	631
England	61	1253	541
Spain	28	454	485
Portugal	24	604	441
Austria	20	375	424
Italy	41	411	419
Belgium	15	466	406
Brazil	22	427	395
Switzerland	17	436	392
Sweden	20	415	378
Germany	34	911	329
Canada	30	518	313
South Korea	26	485	242
Iran	16	209	198
Turkey	15	135	169
Malaysia	22	158	161
Czech Republic	16	105	156
South Africa	9	184	155
Slovenia	7	87	143
Egypt	21	251	141
Denmark	13	90	127
Norway	11	62	120

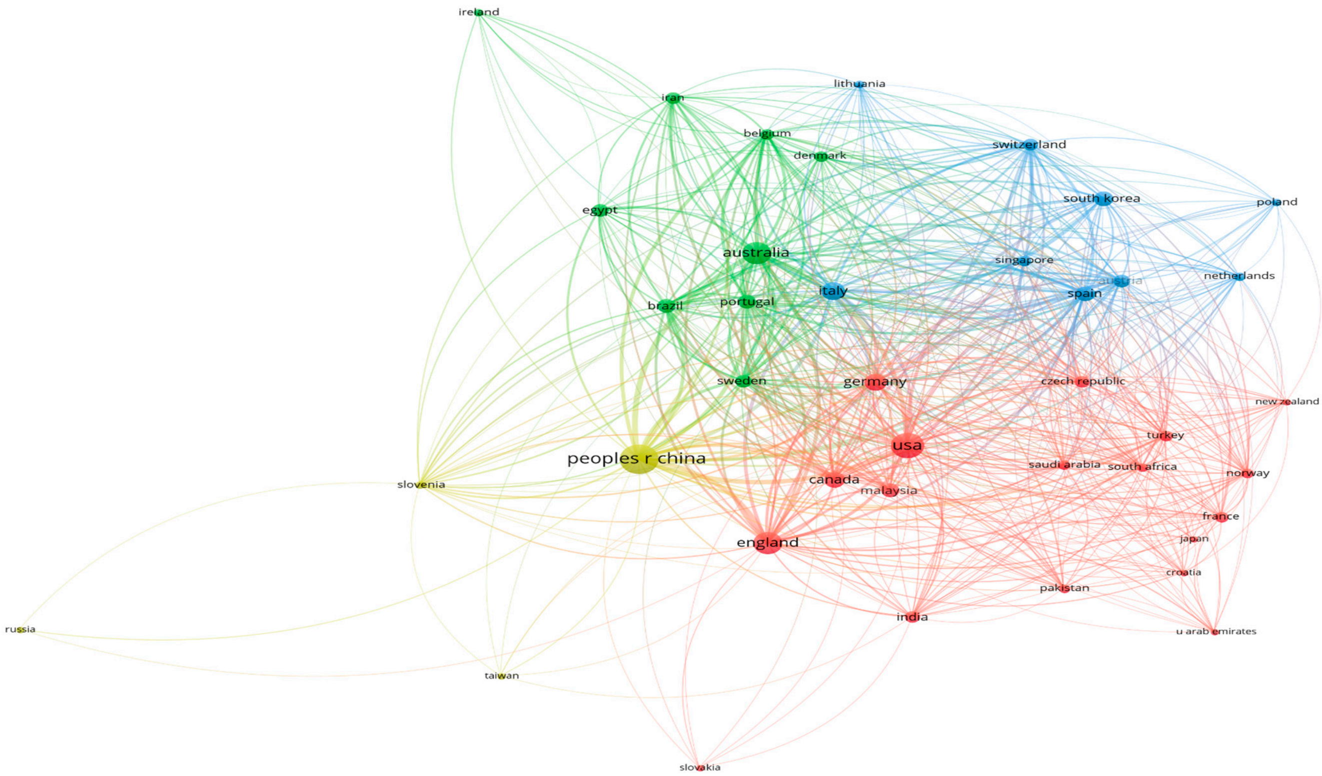

Figure 5. A network of countries/regions.

3. Results

3.1. Building Information Modelling (BIM) and Life Cycle Assessment (LCA)

This section provides a systematic review of the interaction between BIM and LCA tools in a BIM-LCA integration environment. Furthermore, it explores the status of integrating BIM and LCA to detect the unaddressed issues and evaluate how this integration can be applied to BrIM cases that have identical issues. The framework of ISO 14040 [87], which provides a standard procedure for implementing LCA, incorporates four essential steps that must be considered when conducting LCA for any project: (1) goal and scope definition; (2) life cycle inventory analysis (LCI); (3) life cycle impact assessment (LCIA); and (4) life cycle interpretation (ISO, 14044 [88]). Succar [89] considered BIM to be a method that assists the construction industry in achieving its sustainability goals. Many scholars have highlighted the effect of improving and simplifying the process of applying LCA methods to buildings; their findings were directed toward the integration of BIM and LCA as efficient ways of optimizing the performance of LCA. Several studies acknowledged and summarized the importance of BIM tools in helping decision-makers in applying LCA for buildings and choose building materials, construction methods, and building service systems [90–93].

Several studies concerning the integration of BIM and LCA have been published within the last four years; therefore, it is obvious that this area of research has received considerable attention from scholars. Content analysis, as a research tool, helps in extracting textual information from published studies about the combination of BIM with LCA (see Supplementary Information). For instance, Soust-Verdaguer et al. [94] analyzed studies that involve BIM and LCA with a focus on how BIM tools can facilitate the input of data and optimize the data output of LCA tools. The result of that review introduced possible methods for integrating BIM and LCA tools via developing templates and plugins into BIM tools. Nevertheless, this study was published before 2018; therefore, many new studies were not considered.

3.1.1. BIM Model's Input

Defining the physical model is crucial throughout the application of LCA. However, few studies used the level of detail (LOD) of the developed models for building projects, the majority of studies utilized the third level of detail (3rd LOD) to achieve acceptable quantities, shape, size, location, and orientation for energy and emission analysis [95,96]. Soust-Verdaguer et al. [94] believed that the reason behind using the 3rd LOD is that, at this level, most of the relevant materials and components are well defined and therefore appropriate for assessing the environmental impacts of proposed buildings.

3.1.2. LCA Model's Input

Numerous studies have chosen an entire asset as the functional unit to apply the LCA method, while few articles considered partial sections of buildings for this purpose [97–99]. Most of the reviewed studies developed life cycle inventories (LCIs) by creating different databases. The most common types of databases used in these previous studies included the Inventory of Carbon and Energy, ICE, [99,100]; the GaBi database [101]; and the Ecoinvent database [95,96]. These databases were widely employed in carbon modeling and energy simulation software, such as EnergyPlus 9.2 [102] and DesignBuilder [103], while other studies used national databases, like the Swiss Buildings Database [104], the KBOB database [105,106], and the CLCD Chinese database [51,107].

3.1.3. Software Integration and Data Exchange

Integrating BIM with LCA is an efficient way of obtaining necessary information about the construction materials used in BIM models and transferring it to an existing LCA database for LCI outcomes. Rezaei et al. [96] used Autodesk Revit©, Ecoinvent database, and openLCA to perform a comprehensive carbon assessment of a four-story multi-residential building in Quebec, Canada. Based on professional and subjective judgments, the Canadian building norms and standards, and the quality of the materials involved, the Ecoinvent database was initially compared to a list of materials generated in Autodesk Revit© as a BIM tool before it was transferred and processed using the openLCA system. It is obvious that there is a considerable difference between the formats of the data recognized by both the LCA and BIM tools. Therefore, to map the data extracted from a BIM model and import them into the LCA tool, a consistent data format and similar naming conventions for both kinds of data should be established when a link between BIM and LCA tools is to be set [108]. During a data transition, information from BIM models is transferred into LCA tools to determine the LCI results; hence, several studies, such as the ones presented in [24,109], identified six different methods that can be used to bilaterally transfer information and data between BIM models and LCA tools. These methods are listed as follows:

(i) Export the bill of quantities (BOQ) into Excel: it is well known that Microsoft Excel is a third-party tool that is commonly employed in many studies; thus, as part of the integration process, the quantities of materials extracted from BIM tools, like Autodesk Revit© [110] and ArchiCAD [111], are multiplied by the related emission factors provided by LCA tools, such as the Ecoinvent [95,112] and ICE [99,113] databases.

(ii) Export BOQ into dedicated LCA tools: Abbasi and Noorzai [98] presented a BIM-based multi-optimization framework for determining the trade-off between embodied and operational energy. Furthermore, they provided an approach to choosing optimal solutions during the early stage of design. The geometric data and materials' bill of quantity were extracted from Revit, a BIM tool, and subsequently inputted into Athena Impact Estimator, a LCA tool, to calculate the embodied energy of an eight-story residential building.

(iii) The use of LCA plugins in BIM tools: This method has been used to a great extent since Tally, one of the LCA tools, was realized due to its user-friendly interface. Tushar et al. [97] integrated a BIM tool (Autodesk Revit©) with an energy rating tool (FirstRate5) and a Tally plugin into a BIM tool to quantify and compare different design options for a residential building. They compared various design scenarios with different options, including insulation and accessory materials. The results of their study showed that plywood walls had a lower impact on the environment compared to the other types of walls. Furthermore, some studies used sensitivity analysis to determine the factors that have a greater impact on the overall performance.

(iv) The use of visual programming languages (VPL) to evaluate environmental impacts: to assess the emissions of building elements, Marzouk et al. [114] developed an interface in which building data extracted from a BIM model could be transferred to Microsoft Access through a DB link in Autodesk Revit©, a BIM tool, whereas the emission factors could be retrieved from Athena Impact Estimator, as LCA tool.

(v) The use of industry foundation classes (IFC) to transfer the data exported from BIM models to an LCA tool: It is commonly known that the IFC scheme for storing LCA-related information within BIM environments is a workable method for coping with a large volume of data. However, the most recent version of IFC, IFC4, is the only version that makes use of IFC features for simple LCA but not a full LCA [115]. Therefore, more IFC properties should be created if a comprehensive LCA needs to be performed.

(vi) The incorporation of LCA data into BIM objects: In this method, each building's material data stored in the native library of the BIM tool, Autodesk Revit©, are connected to an emission factor obtained from the KBOB database using a unique ID similar to the case reported in the study conducted by Hollberg et al. [105]. The quantities of the materials are obtained using Dynamo through unique KBOB IDs. However, Dynamo is only able to retrieve volumetric data for technical routing components like pipes or ducts. However, several studies considered the creation of new and unique APIs in BIM tools (i.e., Autodesk Revit) for this purpose.

Impact categories are generally grouped into four main areas: (1) the use of natural resources (resource depletion); (2) the effect on human health (human health and safety effects); (3) the effect on the ecosystem (ecological effects); and (4) greenhouse effects (climate change). Each of these effects interacts with the environment at different geographical scales, which can be considered for additional classification of the impact categories, such as global (the depletion of the ozone layer and greenhouse effects); regional (acidification and eutrophication); and local (land use and the formation of photochemical smog).

3.2. Bridge LCA Stages and Frameworks

The life cycle assessment (LCA) approach for a bridge examines all its related activities and processes over its expected life to quantify its energy consumption and potential impacts on the environment, resources, and public health. The reviewed literature in this area revealed that those activities and processes are characterized by diverse scientific scopes, functional units, and system boundaries. However, the typical scopes of these studies encompassed the entire life cycle of bridges, including the material-manufacturing, construction, maintenance and operation, and end-of-life stages [116–121]. Moreover, the research analyzed shows that certain studies did not consider all the scopes pertaining to bridge life cycle assessment, such as the end-of-life stage [122,123]; the maintenance stage [124]; the operation phase [125]; and the use phase [126,127]. Furthermore, the focus of other studies was on a particular scope and specific life cycle boundaries, such as maintenance activities [128] and a material's end-of-life stage [129]. For each of these LCA phases, the specifications of the utilized materials and equipment were given alongside life cycle inventory (LCI) data, which generally consist of background data on the upstream processing models and the related environmental emissions [130]. In any LCA study, the functional unit (FU), which is an essential element, must be clearly defined. The evaluation of case studies related to Bridges' LCA shows the use of a wide range of several functional units, although the two, most commonly single, units used are (i) 1 linear meter of length of a bridge deck and (ii) 1 m^2 of effective bridge surface area, especially when performing comparative LCA studies. However, Guest et al. [116] highlighted that the selection of an appropriate functional unit for infrastructure systems like a bridge is still a challenge. They therefore proposed an LCA result based on several FUs, including (i) FUs that consider only area or distance (i.e., 1 m^2 year; 1 lane m year); (ii) FUs that consider both distance and utilization (i.e., 1 ESAL-m; 1 person m, where ESAL means Equivalent Single Axle Load).

3.2.1. Material Manufacturing Stage

During this stage, raw materials are extracted and processed into a final, usable product for the construction and upkeep of a bridge. The most common manmade materials utilized in bridge structures were found to be concrete and steel [116,118,126,129–132]. The other reviewed auxiliary manufactured bridge materials include asphalt and membrane, epoxy paint, wood, etc. Most of the assessed studies opted to use the Ecoinvent database as their life cycle inventory (LCI) to examine how much energy is consumed during the material manufacturing processes and their impacts on the environment. The three main reasons why most of those studies used this database are as follows: (1) it is frequently updated; (2) it has environmental profile units; and (3) its effectiveness has been verified through research. Alternatively, others utilized LCI data at this phase, which include Gabi [121] and Environmental Product Declarations (EPD) [133]. The LCA results from various studies show that the material manufacturing phase causes the most significant environmental problems in the entire life cycle of bridges.

3.2.2. Construction Stage

During the construction phase of a bridge, the energy consumed and emissions generated from using construction equipment, transporting construction materials, and associated types of work; traveling distance; and the bridge's construction method have a great influence on the environmental effects. In their study, Bizjak and Lenart [125] found that the Ecoinvent database lacks information related to specialized equipment. However, Du et al. [127] evaluated diesel and electricity consumption throughout a building's construction phase using Ecoinvent inventory data. Alternatively, other scholars obtained LCA data for the consumption of diesel-operated machines from different sources, such as manufacturer's and contractor's data [127,134]; databases [118]; the literature [125,126]; and a combination of sources [132].

3.2.3. Operation and Maintenance Stage

The different tasks and activities considered during the design and planning stage of a bridge are included in the operation and maintenance stage. Therefore, Guest et al. [116] utilized data retrieved from a traffic survey conducted by the Ontario Ministry of Transportation in 2015 to forecast fleet composition based on the daily traffic average over the long term. Annual average daily traffic provides an average hourly breakdown of vehicles of a particular range in length to determine the fuel consumed by every vehicle traveled over a bridge per hour over its service life during the operation phase. Previous studies categorized the activities and processes engaged in during the operating and maintenance phase into the following three main categories: (1) maintenance activities; (2) traffic detours; and (3) CO_2 fixed [119,132]. For instance, Penadés-Plà et al. [118] believed that a bridge requires a period of two days for the replacement of concrete mortar cover during the maintenance stage to meet the codes over its 120 years of service life. A review of published studies related to bridge LCA revealed that the type and design of bridges under investigation need specific procedures and types of materials during the maintenance stage. Noticeably, the frequency of maintenance activities, the materials used, and traffic delays have a large impact on every scope of the maintenance process [125]. The main sources of harm to the environment were identified to be the emissions precipitated by the distance of traffic detours and the running distance to avoid traffic detours during the maintenance stage [121,132]. Penadés-Plà et al. [119] added the systems that produce a fixed amount of CO_2 and that are used during the maintenance stage to these sources.

3.2.4. End-of-Life and Demolition Stage

The end-of-life stage involves all the activities related to tearing down a bridge after it reaches the end of its service life. As a result, assessing the environmental impact of this phase must consider the fleet of equipment used throughout the bridge's destruction, the transportation type and the running distance, and the treatment of the generated debris when reuse, recycle, or landfill disposal are utilized as techniques for managing the waste. In the literature, since the methods used were like the ones used during the construction phase, there were neither detailed discussions about the technology and transportation needed in this phase nor details about the environmental impacts. Alternatively, the emphasis was on how to handle the waste generated during the demolition process. Moreover, the literature lacks detailed guidelines and regulations for directing the effective methods to be considered for handling the wastes generated from demolishing bridges because managing these wastes necessitates various acts based on the processes and goals of the treatment [118]. Full recycling at the end-of-life stage was cited as a useful environmental method because it reduces the consumption of original materials and lowers the associated emissions [125]. Hammervold et al. [134] claimed that the requirements for managing the waste produced by construction projects can be met by simply recycling or reusing steel and concrete. At the end of a project's useful life, excess concrete may be crushed and used as aggregate for constructing roads and bridges. Several studies stated that the carbonation of concrete, which is a higher fixer of CO_2, can be achieved by placing crushed concrete in a landfill [109,119,127,130,132]. There was no specific published study in the literature that provided a fixed ratio for recycling steel reinforcement; however, various assumptions were made: for example, Hammervold et al. [134] believed that 100% of the steel they examined could be recycled or reused, whereas Pang et al. [126] reported that only 85% could be recycled. However, Penadés-Plà et al. [118] considered this value to be 71%, while [135] reported a value of 72%. Nevertheless, Penadés-Plà et al. [119] believed that the steel recycling ratio differs according to the location. Du et al. [130] declared that Ecoinvent considers both the energy and the raw material savings from recycling steel rebar during the early stage of a material's production. In regard to this point, it is apparent that the results of LCA lead one to the conclusion that during the whole life cycle of a bridge project, its end-of-life phase imposes the least environmental burden.

3.3. Bridge Information Modeling (BrIM)

BIM is increasingly being adopted as a valuable concept in the construction industry. Its tools can be employed to create shop drawings, detect clashes, estimate quantities, and manage documentation. Bridge Information Modeling (BrIM), on the other hand, is a concept like BIM, but it is specifically applied to bridges. The BrIM tool provides an efficient presentation of bridges that incorporates all the required information during their life cycle [136]. Applying BrIM concepts ensures consistency in acquiring necessary information at the different stages of a bridge's life, starting from design and moving on to maintenance, and this is essential for a bridge's stakeholders because it improves their three key areas of concern (quality, schedule, and cost), speeding up construction while lowering costs [137]. 4D BrIM benefits projects' participants when used during the construction phase for planning materials' delivery, controlling and monitoring a project's progress, and improving construction coordination, schedules, and documentation [138].

At the planning and design stage of bridges, BrIM technology has mostly been used for creating and utilizing 3D bridge models to guide design decisions. To improve the accuracy of modeling designs in 3D, several scholars used parametric modeling for bridges and proposed design guidelines with associated information about 3D modeling to reduce collisions and other modeling issues. Shim et al. [18] modeled each component of a bridge, such as beams, piers, and abutments, by using fundamental parameters like geometric dimensions, which are connected to other elements by a layered architecture of geometry models that are not used by special-shaped components. Lee et al. [20] performed parametric modeling for a bridge's reinforcing bars, while [137] claimed that 3D Bridge models that use digital copies of the Work Breakdown Structure (WBS) and Product Breakdown Structure (PBS) have design improvements and accelerate the learning of construction engineers. Markiz and Jrade [139] developed an integrated 3D model within a BrIM environment, a fuzzy-logic decision support system, and a cost-estimating module to assist in the conceptual design of concrete box-girder bridges. They performed a parametric analysis to measure the system's level of accuracy by exporting BrIM input databases in the IFC file format to minimize the loss of information during the transition process. At the conceptual design stage of a bridge, their developed BrIM system incorporates several bridge maintenance and repair (MR) and replacement (R) solutions to monitor the deterioration of bridges using a multi-criteria decision-making approach (MCDM) to obtain competitive priority ratings. Designing bridges with a beautiful aesthetic can also be carried out using three-dimensional information modeling. Tanner et al. [140] indicated that an elegant solution that satisfies the highest aesthetic requirements could coexist with a contemporary and technologically advanced design. In structural engineering, the environmental, human, and built contexts of civil works are typically not considered during the design stage. Several scholars utilized 3D information models to assess the procedures used to put together a bridge and, afterward, to make suggestions for improvement. Thus, to minimize errors during erection due to some unanticipated types of damage/deterioration in the operation stage, engineers can access and update the data related to the bridge life cycle analysis by using the master digital model throughout a bridge's life cycle [141]. The terminologies and standards of unified modeling are lacking throughout the design process. Employing visualization modeling at the early design stage would yield geometry data for structural analysis [142].

For the construction stage, Lee et al. [20] used a 3D BrIM model to reduce the construction duration by around 4.5 months; the productivity of the site's operation was increased, and it was possible to decrease the workforce by around 6%. Utilizing BrIM could aid in scheduling complex projects, resulting in cost savings between the range of 5% to 9% by minimizing the need for change orders and rework. The initial deployment of 3D modeling would cost about 70% of the total cost; this front-end loading of 3D modeling costs might prevent the wide spreading of its use [143]. Vilventhan and Rajadurai [138] used 4D BrIM to settle piles at various locations within a site that had limited space during the construction stage. Kaewunruen et al. [144] presented a novel 6D BrIM method for the asset management of a bridge structure by integrating 3D model data with cost projection, time schedule, and carbon footprint analysis throughout the duration of the bridge life cycle.

To select the best locations for mobile cranes on the construction sites for a bridge, Marzouk and Hisham [145] proposed a hybrid model combining Genetic Algorithms (GAs) and BrIM that considers various limitations concerning the safety, clearance, existing site conditions, construction schedule, and duration of erecting structural members. Importing the crane model and modeling the erection process might aid in choosing the ideal position for a crane when utilizing a 3D model. Additional studies are required to confirm the applicability of hybrid models. Most of the current bridges were constructed during the 20th century, and accessing their 2D as-built drawings is difficult due to sparse information. It would be challenging and time consuming to create precise BrIM models for numerous bridges by using the information at hand. Furthermore, there are no standardized criteria for BrIM during the operation and maintenance stage, in contrast to the construction of a bridge, which entails specific rules about the levels of complexity (i.e., as-built BrIM can be used during the operation and maintenance stage). To mitigate these problems, a new framework was developed by Xu and Turkan [146] that used camera-based unmanned aerial systems (UASs) to gather and analyze inspection data and a BrIM tool to manage and store all associated inspection data. The findings of their study supported the idea of employing computer vision algorithms wherein high-resolution photographs taken from UASs can be used to visually detect cracks and identify other types of faults. Furthermore, the outcomes supported the use of BrIM for assigning defect information to specific model elements, which allows for the management of all bridge data in a single model throughout a bridge's life cycle and provides a feature for decreasing site visits by negating the need for data re-entry through the aid of cloud computing. Almomani and Almutairi [147] proposed a balanced approach to making decisions related to the management of bridge maintenance under various limitations, such as cost optimization and expert advice [147].

Industry Foundation Classes (IFC) is a model file format used to export and import a BrIM model and its associated information to other tools used in the design, construction, and maintenance of bridges. Park et al. [148] discovered that a semantic-based query addressed to the created IFC-based bridge information model made it feasible to retrieve and extract information for the associated components. Wan et al. [149] proposed the development of a bridge management system (BMS) based on BIM technology and the extension of Industry Foundation Classes (IFC) and International Framework for Dictionaries (IFD) standards. Coding rules were presented for the Chinese bridge industry, and a standard structural modeling approach was presented to quickly build a bridge model in a BIM environment. The proposed system is a web-based BIM and includes a practical BIM-based BMS for a long-span cable-stayed bridge in China. The study demonstrated the potential for IFC-based BIM technology to improve bridge management systems and maintenance efficiency [149]. Dang et al. [141] addressed the information discontinuity between the various stages of bridge projects as well as the existing gap in collaboration between various stakeholders. More data about the performance of digital models must be added. Zhang et al. [150] proposed a new 4D-based model for the life-cycleintegration, modeling, and visualization of infrastructure data. The developed method considers using 4D technology over the construction stage and shows its efficiency for the life-cyclic visualization and modeling of infrastructure data, including with respect to condition evaluations. The technique enhanced the accuracy of maintenance activities by 20–40% and decreased their duration by 30–50%. The lack of standardization in the format and storage of inspection reports makes it difficult for practitioners and researchers to use inspection information for knowledge generation purposes. To address this issue, Hüthwohl et al. [151] proposed an information model and a candidate bound to IFC to classify inspection information for R.C. bridges and standardize its storage in a format suitable for sharing and comparing between different users and requirements. They demonstrated that IFC, in their latest version, could provide adequate functionality for integrating relevant defect information and imagery and presenting a prototypical application as a proof of concept for automatic sharing and comparing of information needed in R.C. bridge inspections [151].

4. Discussion

Bridge Information Modeling (BrIM) can significantly improve the life cycle management of bridges [152]. BrIM is helpful due to its comprehensive built-in database, which is useful for collecting and transmitting data during the different phases throughout the whole life cycles of infrastructures. Accordingly, the exchange-of-information-through-BrIM concept has shown promising results in monitoring complex processes and increasing the management efficiency over the entire life cycle of a project because of the ability of BrIM to consider various options and strategies and reduce the construction costs and duration of projects during a comprehensive analysis of qualitative and quantitative information.

Initiated by the concept of BIM, considering 4D (time) and 5D (cost) modeling in bridge and infrastructure projects can improve the quality of design and collaboration with respect to the scope, scale, and complexity of such types of projects at the conceptual and detailed design stages [18]. Markiz and Jrade [153] took into account the features of bridge information modeling to conduct a novel fuzzy logic approach for the design of a concrete bridge to decrease its construction costs and simplify the collaboration between stakeholders. The construction of bridge projects requires high investments and comprehensive work. Using BrIM concepts and tools provides more accurate quantity take-offs (QTO) with which to estimate the construction cost of bridges [154], which can lead to optimal budgeting and reduce conflicts and delays. The capabilities of BrIM in generating cost estimates hold many benefits for further analysis in a shorter time.

This study provides the following outcome: although BIM has valuable features for various construction projects, using BrIM for bridge engineering offers distinct capabilities. In terms of the geospatial context, bridges are usually incorporated with natural or urban landscapes, which, using BrIM, can better integrate geospatial data compared to BIM platforms. Regarding regulations, bridges are more subject to standards and regulations for meeting safety and performance requirements. Using BrIM can assist in improving performance with respect to the standards in the modeling and analysis process. Moreover, because of the different components, structures, and geometries of bridges, BrIM can recognize these aspects and provide a tailored framework for bridge design and construction.

Notably, the extended lifecycle of bridges and the need for ongoing repair, maintenance, and monitoring necessitate the use of BrIM, which considers the entire lifecycle of projects for decision making and asset management. Moreover, interdisciplinary collaboration for bridge projects is influential because of various stakeholders, such as engineers, designers, and regulatory agencies. In this regard, BrIM improves collaboration by providing an integrated platform that promotes better coordination and reduces errors. Considering the abovementioned points, BrIM as a specific version of BIM, is more beneficial for bridge engineering, and providing a BrIM platform with respect to LCC and LCA can lead to savings in cost and time, thus improving quality, reducing safety problems, and reducing environmental impacts during a bridge's lifecycle.

The three main methods applied to integrate LCC and LCA with BrIM are as follows:

- Utilizing existing BrIM tools, such as Autodesk Revit, CSiBridge, Autodesk Infraworks, Autodesk Civil 3D CAD, and Tekla Structures to generate bills of quantities and other relevant data;
- Exporting the data from a BrIM tool to an external tool;
- Involving data and information in the BrIM environment.

The first method focuses on exporting information, like the quantity of materials and energy consumption, from the BrIM model to Microsoft Excel for additional calculations [99]. This method makes the calculation process clearer for the management team. However, it requires more time to execute the calculations and holds some compatibility problems because of the use of different types of software. The second method concentrates on exporting the data from the BrIM model to an external tool to implement the calculations on a new platform. Finally, the third method is directly applied in a BrIM environment [155]. The results of the second and third methods are visualized in a user-friendly platform, allowing engineers to easily modify and update the associated information and data. Notably, the integration of LCA and LCC with BrIM can facilitate design by obtaining fast and reliable outcomes for the LCC and LCA analysis and assessment at the early stages. The results of this study are demonstrated in Figure 6, which shows the inputs needed to implement LCA and determine LCC for bridge projects.

In Figure 6, the various stages of a bridge LCA provide a structured framework for assessing the environmental and economic impacts of bridge projects. It is within these stages that critical inputs are identified for a thorough LCA analysis. Drawing inspiration from the work of [156], required inputs and examples have been outlined, shedding light on their significance for each LCA process.

In the initial stage of "Bridge construction input definition based on the design model", the essential inputs encompass assumptions, system boundary definition, functional units, and a comprehensive array of materials and activities. These inputs are drawn from the entire lifecycle stages of bridges, spanning from design to pre-construction and material transportation. The BrIM integration method, originating primarily from the planning and design phase, plays a pivotal role in harnessing data integration. It offers functionalities such as material quantity take-off, the ability to determine the locations of manufacturers, and access to material cost databases, thereby enhancing decision making clarity and efficiency.

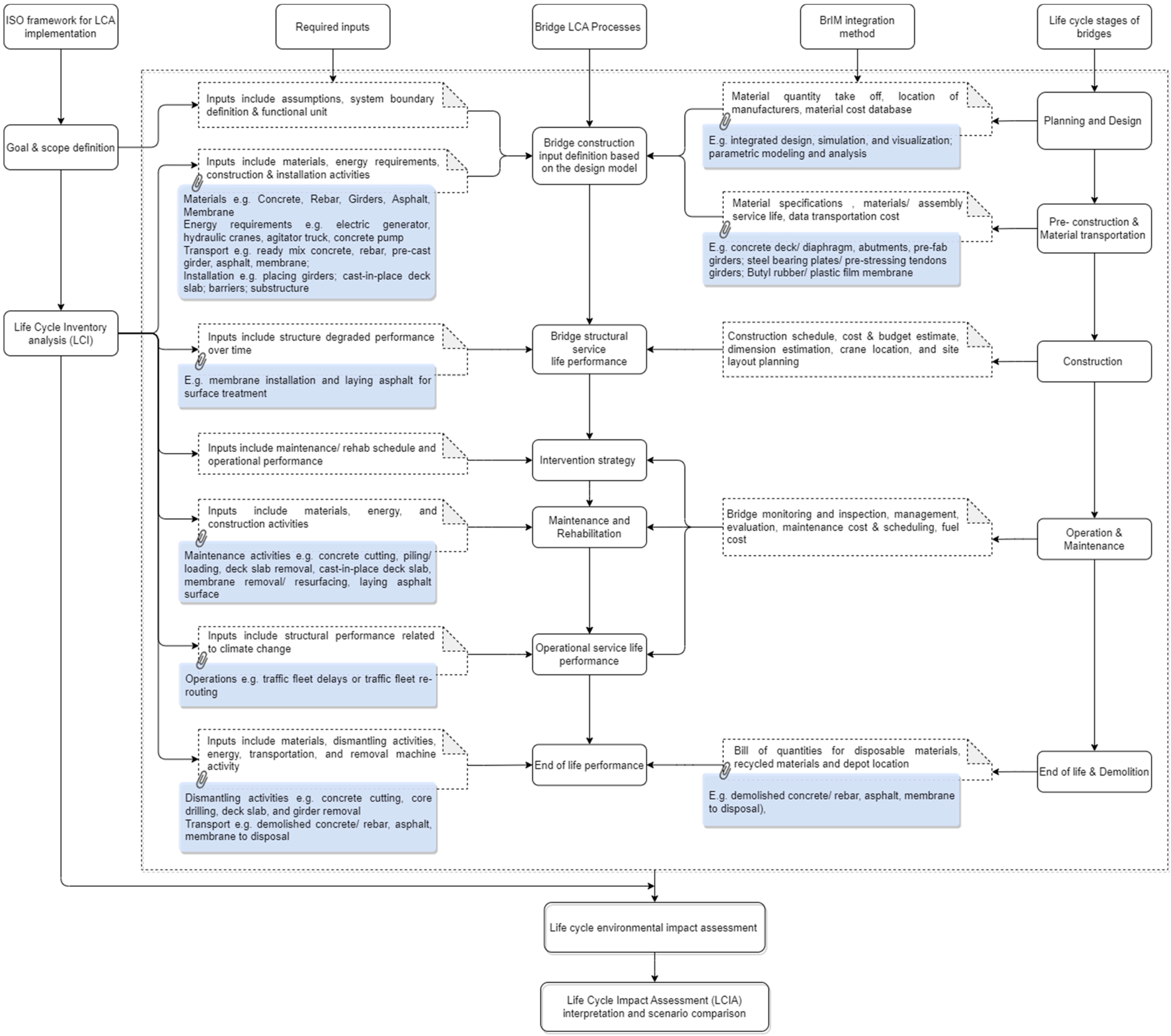

Figure 6. Graphical presentation of the required inputs for bridge LCA-LCC processes in each life cycle stage.

Moving forward to the "Bridge structural service life performance" stage, the focus shifts to inputs that delineate structural degradation over time. These inputs are derived from activities within the construction phase, and BrIM integration ensures precision through the 4D scheduling of construction activities and material quantity take-offs. This integration optimizes construction processes with careful attention paid to LCA and LCC analysis, culminating in a precise digital representation of the completed bridge with the inclusion of LCA and LCC data.

Proceeding to the "Intervention strategy", "Maintenance and rehabilitation", and "Operational service life performance" processes, the corresponding inputs revolve around maintenance schedules, operational performance, and structural performance related to climate change. Here, the BrIM integration method draws extensively from the operation and maintenance stage of a bridge's lifecycle. It functions as an asset management system, meticulously tracking the performance of bridge elements over time and integrating LCA and LCC data to predict maintenance needs and optimize schedules. Additionally, the inclusion of safety-monitoring systems within the BrIM environment enhances anomaly identification while considering LCC implications, further bolstering the bridge LCA platform's utility.

In the "end of life performance" process, the corresponding inputs encompass materials, dismantling activities, energy, transportation, and removal machine activities. The BrIM integration method, rooted in the end-of-life and demolition stage of a bridge's lifecycle, focuses on bills of quantities for disposable materials, recycled materials, and depot locations. This integrated approach to decommissioning minimizes costs and environmental impacts, producing invaluable documentation and archives for future decision-making processes. Overall, the proposed BrIM-LCA framework for bridge assessment represents a significant advancement in the construction industry. It streamlines decision-making processes, enhances data integration, optimizes construction activities, predicts maintenance needs, and minimizes environmental impacts. By embracing the synergy between BrIM, LCA, and LCC, a powerful tool for designing and managing sustainable and economically sound bridge projects can be unlocked. In this endeavor, the inputs and integration methods across various stages have been delineated, highlighting the interconnectedness and cohesiveness of this comprehensive approach. The future of bridge infrastructure lies in this integrated framework, where data-driven decisions foster a sustainable and resilient built environment.

5. Conclusions

In this study, we performed a comprehensive literature review along with bibliometric and detailed content analysis focusing on the areas of BIM, the integration of LCA and LCC, BrIM, and bridge LCA. The major goal of this paper was to investigate the potential outputs that can be retrieved from the literature concerning the integration of BIM, BrIM, LCA, and LCC so that they can be considered as inputs for bridges' LCA. The visual term co-occurrence network, which is provided in this study, supports its set objective to explore and the literature and analyze its gaps to discover the functionalities of BrIM if integrated with LCA and LCC for bridges over their life cycle. The following conclusions were drawn using this literature review methodology:

(1) To attain a better and more detailed understanding of the essential requirements for achieving the above-mentioned integration, a thorough evaluation of the published studies centered on the integration of BIM and LCA; BIM and LCC; and BIM, LCA, and LCC was executed. To perform an efficient LCA for bridge projects, a thorough analysis of the published methodologies was carried out with an emphasis on the objectives and scopes and the functional units to be considered at each stage of a bridge's life, spanning from the material production stage through to its end-of-life stage (EOL). Then, the idea of BrIM was carefully reviewed based on the relevance of BIM concepts during each stage of a bridge project.

(2) BrIM technology is a digital presentation of the physical and functional characteristics of a bridge that involves its geometry, materials, and behavior. BrIM can facilitate the creation of detailed digital models of bridge projects, which can be used to evaluate different design alternatives and construction successions.

(3) LCC is the basis for evaluating the costs of different design and construction options over the whole life cycle of projects, including their operation and maintenance costs. LCA is an efficient context for analyzing the environmental impact of a project over its entire life cycle, including the impact of the materials used, the energy consumed, and the waste generated. The integration of LCC and LCA with BrIM helps designers, engineers, and contractors to conduct accurate evaluations of a bridge's performance and assessments of its environmental impact over its anticipated life. This integration can facilitate the decision-making act during the design and construction phases and lead to better maintenance and repair strategies throughout the bridge's service life.

(4) Furthermore, integrating LCC, LCA, and BrIM can enhance the collaboration and communication between various stakeholders who are involved in the design and

construction of a bridge project. BrIM provides a platform for stakeholders to share and visualize data that can support the process of making efficient decisions. Joining LCC and LCA with BrIM assists decision makers in evaluating different scenarios and alternatives in a virtual environment to determine the most cost-effective and sustainable options. Overall, the integration of LCC, LCA, and BrIM helps individuals make better decisions, thereby decreasing the environmental impact and improving the performance of bridge projects.

(5) With respect to the abovementioned review of the literature, which focused on the evaluation of integrating BrIM with LCA and LCC, we recommended that researchers proceed with an additional evaluation and analysis that would be centered as a roadmap for developing a prototype model for bridge LCA and LCC within a BrIM platform. This roadmap can guide the way for the implementation of a standalone integrated model that acts as a platform for integrating BrIM, LCA, and LCC, but this was not the focus, to the best of our knowledge, of any of the previous studies. Furthermore, using optimization frameworks that incorporate BrIM, LCC, and LCA can be considered for future studies as well. The proposed framework permits the development of a more detailed approach to making accurate and effective decisions related to the construction of bridge projects by considering both the costs and the environmental impact over the long term. To further enrich the scope of future research in this domain, the potential implications of capital investment required for the adoption of digital technologies like the proposed framework can be investigated. While this study has explored the integration of BrIM with LCA and LCC, its future expansion will concern understanding the impact of capital investment on construction projects and its importance. The extended framework will also consider budget constraints and financial conditions, ultimately leading to more sustainable and cost-effective measures. Optimization frameworks that incorporate BrIM, LCC, and LCA can be used to assess different design and construction options and determine cost-effective and sustainable measures based on budget limitations and financial conditions for such types of projects.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su152015049/s1. Table S1. List of reviewed articles (BIM-LCA integration). Table S2. List of reviewed papers (BIM-LCC integration). Table S3. List of reviewed papers (BrIM).

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