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Review

Digitalization and Sustainability in Linear Projects Trends: A Bibliometric Analysis

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Abstract: Linear infrastructure projects, including roads, tunnels, and railroads, are vital for the socioeconomic advancement of regions and nations. Given their large scale, these projects require significant resources, leading to substantial environmental impacts and demanding the collaboration of professionals from multiple disciplines. In this context, it is essential to adopt strategies that favor digitalization to enhance the sustainability of such projects by automating the analysis of various alternatives. Despite the proliferation of studies in this area, there needs to be more research synthesizing the main trends in digitalization and sustainability in linear projects. Given this knowledge gap, this study focuses on identifying and analyzing the main trends in digitalization and sustainability in the context of linear infrastructure projects. To this end, a comprehensive bibliometric analysis of a selected set of papers has been carried out. The research method follows five main steps: (1) scope definition, (2) selection of bibliometric analysis techniques, (3) data collection, (4) bibliometric analysis execution, and (5) evidence analysis and synthesis. An analysis of 419 documents was done, applying performance analysis and scientific mapping techniques. The results reveal that trends in digitalization and sustainability in linear projects can be categorized into five main clusters: road construction, road administration, life cycle analysis, digitalization of linear infrastructure, and sustainable development, leading this line of research towards computer-aided design technologies such as BIM, GIS, and computer vision to study sustainable development throughout the whole life cycle analysis of linear infrastructure projects.

Keywords: linear projects; road infrastructure; sustainability; digitalization; digitization; trends; bibliometric

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1. Introduction

The development of infrastructure projects forges the structural tissue and connects the community, making them an integral part of the socioeconomic development of nations [1]. Infrastructure projects are related to modernization activities to increase the productivity of different economic sectors and the community's well-being [2]. Projects such as highways, bridges, buildings, diverse transportation channels, and essential utilities are emblematic of society's vital arteries [3]. The impact of infrastructure projects on economic and social development cannot be overstated, as they connect communities and provide essential public services that improve the quality of life for city and regional residents [4]. Emphasizing their lasting significance, it is crucial to ensure these projects perpetuate value throughout their extensive life cycle, potentially spanning several centuries [5]. This calls for a rigorous, holistic assessment to maximize their economic, social, and environmental sustainability impacts.

While infrastructure projects manifest in various forms, they are generally bifurcated into vertical and horizontal categories based on their objectives. Both linear (horizontal) and vertical infrastructures indubitably bolster community development, but they exhibit distinctions in execution contexts and challenges. Linear projects, such as rural and urban roads, tunnels, railways, and utility networks, constitute essential infrastructures that trace the connective fabric of regions. In contrast, vertical projects are predominantly associated with building structures and are fundamental pillars of the urban and architectural landscape [6]. Linear infrastructure necessitates more intricate planning than its vertical counterpart, demanding increased investments, precision engineering, and cohesive coordination across the value chain [7]. Assessing sustainability poses several challenges that are unique to this field. One of the main difficulties is the complexity of incorporating ecological principles into linear projects. This is due to such projects' inherent variability, making it challenging to develop comprehensive evaluation systems [8]. Linear projects have a significant environmental footprint, primarily due to the need for vast land acquisition [6]. Therefore, it is crucial to prioritize environmental and social sustainability to reduce linear projects' negative environmental and societal impact [9,10].

Linear projects are of great importance, which has led to the development of a wide range of studies. In recent years, research on bridges, roads, and railways has become essential to improve all life cycle stages, aiming to combine safety, efficiency, and sustainability [11,12]. Implementing various methodologies and technologies has improved the planning and management of different types of linear projects, resulting in optimized resources and time [13,14]. In terms of materials, the introduction of self-repairing materials and high-strength metallic alloys has increased the useful life and resistance of bridges, tunnels, and roads [12,15,16]. In the field of railways, research has focused on developing infrastructure systems that enable the operation of magnetic levitation trains and the optimization of railway networks' interconnection to improve mobility and reduce travel times [17,18]. In urban spaces, the incorporation of intelligent systems for constant infrastructure monitoring [19], using sensors and Artificial Intelligence algorithms connected to the internet and under the focus of smart cities, has enhanced various issues' improvement and maintenance schedules, ensuring the safe operation of linear projects [20,21].

Various methodological and technological approaches have been developed to address the challenges faced in linear infrastructure projects [10,22]. Some methods incorporate the principles of commonly used sector tools such as Building Information Modeling (BIM) to promote rational resource consumption, increase project durability, and enhance positive impacts throughout the project life cycle [23]. These strategies aim to reduce carbon emissions while highlighting the natural landscape's qualities and cultural value [24].

With Industry 4.0 (I4.0), the construction industry has access to various technologies that can be utilized across different fields. Numerous authors have attempted to classify I4.0 technologies based on their characteristics and services, which can benefit the construction industry. Construction 4.0 is a term used to describe the digitalization of the construction sector using Industry 4.0 technologies such as digital twins (DTs), the Internet of Things (IoT), and artificial intelligence (AI), among others, applied to construction and infrastructure. Therefore, Construction 4.0 is defined as "the digitalization of the construction sector" [25]. Although the relationship between the concepts of Industry 4.0 and the construction sector is new and emerging for the first time in 2014, there is growing interest in this field of research [26,27]. As a result, the digitalization of linear projects has led to the adoption of advanced methods to improve sustainability throughout their life cycle. This technological transition not only enhances the execution of these projects but also establishes more responsible and efficient environmental and operational management.

Digitalization of the construction sector has been triggered by the "digital revolution" later than other industries. Until recently, construction organizations offered services based on common data environments (CDE) to engage in collaborative frameworks and vendor-neutral data exchange, focused on better BIM management through a digital twin [26]. BIM has become the most precise application of digitalization in construction, relying on

digital platforms to gather people, processes, and technology, and has most recently been applied to linear infrastructure projects [28–31]. The use of digital twins in linear projects has brought about a revolutionary change in how infrastructure planning and execution is done since this concept (originally from the Internet of Things term) has turned the project perspective into a long-term use of technology beyond delivery and closure. These virtual representations allow projects to be analyzed and optimized in detail during the initial phases before construction begins [32]. This digital approach simplifies the decision-making process and enables automated exploration of alternatives that prioritize sustainability and energy efficiency. Incorporating artificial intelligence (AI) in these digital twins enables the generation and evaluation of multiple project configurations [33,34], offering a simulation space in which infrastructure requirements are balanced with sustainability needs. Once through the construction phase, the digital twin transcends its initial function, becoming a digital database through integration with Internet of Things technologies. Sensors scattered throughout the infrastructure feed this digital model with real-time data [35], enabling operational adjustments that improve efficiency and strengthen the environmental and social commitments of the projects.

The influence of linear projects on the environment is indisputable, which underlines the need to incorporate methodological and technological approaches that move towards sustainability [36]. In this scenario, digitalization emerges as an alternative with a wide potential, allowing not only the analysis but the iterative optimization of configurations to improve the sustainability of projects. Although the construction field has witnessed a rising wave of digitalization, reflected in a profusion of recent publications, there is still a lack of studies that synthesize the trends of digitalization and sustainability applied to linear projects. Given this knowledge gap, this study has two main aims: (1) Identify the components that constitute the research field of digitalization and sustainability in linear infrastructure projects and (2) Analyze the methodological and technological trends of digitalization and sustainability in linear infrastructure projects. This paper is divided into six main sections. Section 1 is the introduction. Section 2, Literature Background, is divided into three subsections: Digitization in Linear Projects, Sustainability in Linear Projects, and Bibliometric Studies in Linear Projects. Section 3 is the Research Method, divided into five subsections: Scope Definition, Selection of Bibliometric Analysis Techniques, Data Collection, Bibliometric Analysis Execution, and Evidence Analysis and Synthesis. Section 4 is the Result, divided into four subsections: Performance Analysis, Thematic Map, Cluster Analysis, and Trend Analysis. Section 5 is the Conclusions, and the sixth is Limitations and Future Research.

2. Literature Background

2.1. Digitalization in Linear Projects

Digitalization has been promoted in linear projects through various technological approaches related to the fourth industrial revolution. When implemented in construction projects, this is known as Construction 4.0, a confluence of digital and physical trends and technologies that promise to reshape how built environment assets are designed and materialized [25]. Several authors agree that to reach Construction 4.0, the confluence of the following two strategies is necessary: (1) digitalization, as data management in digital format using Industry 4.0 tools and technologies, and (2) industrialization, as construction automation processes under the use of unconventional technology and methodologies [37–39]. This study focuses on the analysis of the first strategy. Digitalization in linear infrastructure has been primarily based on adopting BIM in various linear projects. Eastman et al. [40] define BIM as "a verb or phrase to describe tools, processes, and technologies that facilitate digital, machine-readable documentation about a construction project, its performance, its design, its construction, and subsequent operation." BIM can also be described as a digital representation of a creative plan. It has a digital database store that contains large amounts of planning information and enables relationships and participation among competitors

and information sharing [41]. The dominance of virtual and accurate BIM information improves general plan performance for construction projects [42,43].

The following studies are among the main advances in adopting BIM in linear projects. Huang et al. [44] analyzed the feasibility of implementing dynamic and real-time BIM developed during the alignment design and compared it to traditional methods. The results show that implementing BIM can bring essential benefits such as (1) simplifying track alignment design processes, (2) increasing the capability of computer-aided design, (3) automating the design processes, and (4) reducing the design periods. Zhao et al. [45] show an approach for roadway route optimization based on integrating Geographic Information Systems (GIS) and BIM, using a method based on a Genetic Algorithm (GA) and three-dimensional models to idealize locations. This enables effective and efficient planning and design processes, reduces gaps in incorporating road project information with other surfaces, promotes communication and coordination, minimizes design errors and hazard management, and improves pricing and schedules.

Tang et al. [46] propose a construction verification and unification framework to improve the application of BIM in road engineering. The analysis provides innovative and practical road design bonding and pavement research solutions. Collao et al. [47] generate a model that integrates current traffic data and vehicle fleet statistics from visual programming tools and BIM to centralize databases from different sources. The proposed model is designed to estimate emissions and carbon footprint based on the emission factors recommended by the European Environmental Agency (EEA). The result of this model is an automated platform that enables the estimation of road traffic emissions (with a 72% accuracy rate compared to estimates made by a similar report). This platform automates the communication between equations and databases required for estimating road traffic emissions, making the estimation process faster and more efficient.

Vignali et al. [48] adopted the I-BIM approach to improve highway sections in Northern Italy and identify the benefits of implementing the tools "Autodesk AutoCAD Civil 3D" and "Revit Structure" on existing infrastructure. As a result of the implementation, they identified the I-BIM approach as a powerful tool to optimize and validate road plans and provide a visual means for infrastructure in a real 3D environment.

McDonald et al. [49] reviewed the current state of the art of information transmission and data acquisition schemes for Road Traffic and Traveler Information Systems (RTTSI). Cantisani et al. [50] also designed four scenarios for a three-level intersection in Italy. They aimed to improve capacity and service level and reduce delay and queuing emissions. They used the Civil 3D tool, VISSIM 11, and SimaPro to simulate operational performances and assess carbon footprints. The study also estimated construction, maintenance, and usage costs.

Digitalization applications have recently been found in bridge and railway projects. Poku-Agyemang et al. [51] propose a workflow for digitalizing bridges from 2D plans based on reconstructing parts using 3D point clouds and merging the reconstructed elements to create a scaled 3D object. The method was evaluated on three bridges over the Dreisam River in Freiburg, Germany. As a result, they obtain an intermediate 3D model object with potential BIM applications, such as bridge monitoring and evaluation. Li et al. [52] proposed a Bridge Maintenance System (BMS) that utilizes Building Information Modelling (BIM) to manage bridge defect information digitally. Their system was tested on the Cocodala Bridge in Xinjiang, China, and allows for visualization of bridge defects, evaluation of technical conditions, and recommendations for bridge maintenance methods. Kaewunruen et al. [53] developed a digital twin system integrating BIM for life cycle analysis and railway bridge operation, maintenance, and management. They presented a case study of the Minnamurra Railway Bridge in Australia and demonstrated the feasibility of digital twin technology for railway maintenance and resilience optimization. Their system aims to improve sustainability, reduce emissions, and increase the resilience of the railway bridge. Sresakoolchai et al. [54] developed deep machine learning models using co-simulation to implement three-dimensional recurrent neural networks. The study has

demonstrated the potential of machine learning and BIM for predictive maintenance, which can enhance the safety and cost-effectiveness of railway maintenance.

Digital transformation under the Industry 4.0 scope has seen significant progress in recent years, for it requires full attention from academia and the private and public sectors to identify the unforeseen and unintended consequences of triple-bottom-line (TBL) sustainability: environmental, economic, and social aspects in the linear infrastructure projects [55]. There is a gap in the literature regarding how digitization and automation can be effectively integrated throughout the project life cycle from design to maintenance. While some studies emphasize the benefits of digital technologies, there is a need for a holistic assessment and methodology that combines digitization and industrialization strategies to maximize sustainability and efficiency in these projects. This area remains under-researched and requires further investigation.

2.2. Sustainability in Linear Projects

Sustainability has become a fundamental principle in the development of the built environment. While its application is focused primarily on building construction, there is growing evidence in the literature that sustainability is also gradually being adopted in civil infrastructure projects [56]. Implementing the TBL sustainability analysis in some studies has enabled the transfer of sustainability from a concept to numbers and indicators that quantify and optimize it to improve environmental, economic, and social performance [24]. Sustainable construction involves the protection of ecosystem services, reduction in resource consumption, optimized use of renewable resources, and reduction or elimination of the use and generation of toxic elements [57]. Furthermore, sustainability is centered around the health and well-being of users, the improvement of habitats, the rational use of resources such as energy and water, the reuse of materials, and the reduction of contamination risks to the natural environment [58]. Maintenance strategies for concrete structures in linear projects are also essential [59].

There are several relevant and applicable terms in the context of sustainability in construction projects, such as low-impact development (LID), green infrastructure (GI), and nature-based solutions (NBS). LID, for example, is a set of practices that mitigate the harmful impacts of climate change, efficiently manage urban rainwater, reduce runoff loads, rehabilitate the functions of the ecosystem, and reduce energy consumption and greenhouse gas emissions [60]. GI enhances the resilience of ecosystem services, reduces vulnerability to natural hazards, and generates a built environment tailored to the specific needs of national, regional, or local planning [61]. NBS aims to use the principles of nature to address challenges such as climate change, resource management, and disaster risk [62]. However, financial and governance constraints hinder the large-scale implementation of NBS [63].

Several investigations have been conducted to analyze the impact of the fast growth of the construction industry and urban development on the environment. According to Shen et al. [64], the rapid population growth in China has exceeded ecological limits. Therefore, the nation has been forced to generate more appropriate policies and strategies for urban planning and infrastructure development. This has resulted in positive outcomes for constructing linear projects, such as roads, train rails, and transportation projects in general. However, the sustainability measurement in infrastructure projects is not standardized, and it is challenging to achieve an analysis framework that includes the vast diversity of possible projects in this field [65]. Consequently, the current approaches to analysis models and sustainability measurement methods reported in the literature are grouped depending on the type of project or scope contemplated during the life cycle.

Shen et al. [66] developed a sustainability assessment model throughout the life cycle of construction projects based on a system dynamics method, while Ugwu et al. [67] proposed a measurement system that covered only the operation stage of the projects. Most of the evaluation processes of sustainability in infrastructure projects have focused on social and environmental factors during the construction and operation phases, which reveals

a significant lack in the initial stages, generating weakness in the planning of this type of project. Ibrahim et al. [68] identified four main parameters that bring together this challenge: communication and collaboration, design objectives, institutional frameworks, and regulations. Although not many authors have studied models to quantify sustainable variables in linear projects, Bryce et al. [69] present their investigation related to a review of rating tools for systematic assessment of road pavement sustainability. Linear infrastructure projects also face other issues, such as risk management, for which Keir et al. [70] affirm that trust between actors and information transparency is crucial in conflict resolution. The conflicts may be directly or indirectly related to the acquisition and use of land, environmental damage, noise and vibration generation, and route selection, among others [71].

The life cycle analysis (LCA) methodology evaluates vertical and linear infrastructure projects' environmental, social, and economic impact. It is essential for planning and designing sustainable projects, such as bio-infiltration rain gardens, which can reduce adverse environmental and human health effects while providing economic benefits. Flynn and Traver [72] used LCA to assess the impact of a rain garden on the Villanova University campus. Similarly, Aranda et al. [73] investigated how to minimize shadow areas in mountain roads to improve infrastructure sustainability. Tan et al. [74] studied how implementing sustainable practices in infrastructure projects can impact business competitiveness. They provide a guide for contractors to improve their sustainability performance. Additionally, Kaewunruen et al. [75] found that combining lifecycle management and digital tools, such as BIM 6D, can lead to better results in infrastructure construction, as they observed in their study on bridges. Chini et al. [76] analyzed green infrastructure programs in 27 municipalities in the United States. They found that effective green infrastructure planning requires participation and communication with the community, well-defined policies, and a maintenance plan.

While there is a lot of valuable research on sustainability in infrastructure projects, it is essential to link and integrate these studies to maximize their impact and achieve better results for linear projects. For example, it is necessary to consider using materials with a lower ecological footprint, implementing technological tools for efficient resource use, reducing waste and emissions, and implementing simulations to improve infrastructure functionality. Although sustainability research has been done on linear projects, there is a gap in standardizing measures and analysis models that cover all life cycle phases of linear infrastructure projects. The current methods focus on specific phases, such as construction and operation, and fail to include critical aspects in the initial and final stages, which weakens the overall sustainability planning and evaluation. Moreover, there is a need to explore the effective integration of technological tools and methodologies, such as BIM Life Cycle Analysis (LCA), to improve functionality and sustainable performance throughout the project.

2.3. Bibliometric Studies in Linear Projects

Several studies apply bibliometric review methodologies to guide research on linear projects. The primary studies are collected in Table 1, where most of the studies are classified into topics "Highway Safety", "Transport and Traffic", and "Smart Cities". The symbol ✓ represents that the study has addressed the field of research to which it refers. The field of Highway Safety has different studies standing out: Angarita-Zapata et al. [77] present a bibliometric and experimental analysis of the use of machine learning (ML) and automated machine learning (AutoML) in predicting the severity of traffic accidents. Haghani et al. [78] found trends in traffic accidents. Ospina-Mateus et al. [79] conducted a bibliometric analysis of motorcycle safety to identify significant publications focusing on risk factors associated with road crashes and their consequences. Zou et al. [80] analyze the variables that influence traffic accidents. In the "Transport and Traffic field," bibliometric studies have been focused on the review of traffic control approaches developed on highways [81], applications of big data algorithms in intelligent transportation systems [82], and applications of blockchain-based systems in transportation [83].

About Smart Cities, Lozano et al. [84] focus on a bibliometric review of vehicular communications in smart cities. Technologies such as V2X (Vehicle-to-Everything), I2X (Infrastructure-to-Everything), and P2X (Pedestrian-to-Everything) were analyzed, and they found these enabling interactions and information exchange among vehicles, infrastructure, pedestrians, and traffic management systems to enhance mobility, road safety, and transport efficiency. On the other hand, Kasznar et al. [85] analyze the issues and challenges posed by infrastructure in smart cities within the context of urbanization processes. It focuses on traffic control, transport network design, IoT integration, big data analysis, and sustainable construction. Escobar et al. [86] highlight the importance of academic studies in Italy, particularly at the Polytechnic University of Milan, regarding the convergence of Information and Communication Technology ICT and sustainability in addressing urban mobility issues.

Other studies focus on research fields such as "Highway Construction", "Highway Planning", "Intelligent Transportation", "Unmanned Aerial Vehicles (UAV)", and "Technologies in construction". However, the absence of specific studies addressing digitalization and sustainability in linear projects throughout their lifecycle is evident. Therefore, this study aims to bridge this knowledge gap through the application of bibliometric analysis. This approach aims to identify the components that constitute the digitalization and sustainability research field in linear infrastructure projects while also analyzing the methodological and technological trends related to this area.

Table 1. Bibliometric studies focused on linear projects.

Id	Study	Highway Construction	Highway Planning	Highway Safety	Transport and Traffic	Intelligent Transportation	Smart Cities	Unmanned Aerial vehicles	Vehicular Issues	Digitalization	Technologies in Construction	Sustainability	Life Cycle Management
S_1	Zapata et al. [77]			✓									
S_2	Milad et al. [78]			✓									
S_3	Kumar et al. [87]								✓				
S_4	Rodríguez et al. [88]							✓					
S_5	Siri et al. [81]				✓								
S_6	Kaffash et al. [82]				✓								
S_7	Abdelmageed et al. [89]	✓											
S_8	Astarita et al. [83]				✓								
S_9	Mateus et al. [79]			✓									
S_{10}	Zou et al. [80]			✓									
S_{11}	Domínquez et al. [84]						✓		✓				
S_{12}	Muñoz et al. [90]					✓							
S_{13}	Castañeda et al. [91]		✓										
S_{14}	Gao et al. [92]						✓			✓			
S_{15}	Li et al. [93]										✓		
S_{16}	Balaji et al. [94]											✓	
S_{17}	Lee et al. [95]									✓			
S_{18}	Kasznar et al. [85]						✓						
S_{19}	Escobar et al. [86]						✓					✓	
S_{20}	This study									✓		✓	✓

3. Research Method

Linear projects generate a notable environmental impact and various challenges for project managers, highlighting the need to incorporate sustainability and digitalization at all life cycle stages. Thus, conducting an exhaustive analysis of trends associated with adopting sustainability and digitalization in linear infrastructure projects requires methodologies capable of handling vast volumes of information. For this reason, this study employs bibliometric analysis, a research strategy recognized for unraveling scientific production in a specific field of study [96]. Based on the quantitative examination of various bibliographic sources, this technique aims to decode patterns, highlight trends, and reveal underlying relationships in scholarly publications. In contrast to the systematic review, which focuses on collecting, critically evaluating, and synthesizing all relevant scientific evidence on a specific research question [97], bibliometric analysis focuses on the quantitative evaluation of scientific output. Therefore, due to the large number of papers published on digitization and sustainability in linear projects, this study utilizes bibliometric analysis to take advantage of the characteristics for analyzing large volumes of data.

The importance of bibliometric analysis is based on its ability to detect emerging areas of research and rising trends in scientific production. This comprehension is procured via studying the recurrence of specific terms and keywords. The process enables the elucidation of emerging thematic areas and anticipating prospective research directions [98]. Thus, discernment is achieved by analyzing the frequency of specific terms and keywords in the examined publications, which benefits researchers as it allows them to identify areas of study with the potential to adapt their work to the demands and needs of the scientific community.

This study follows the methodology for bibliometric analysis proposed by Donthu et al. [98] and adopted by Castañeda et al. [91], which is organized into five consecutive phases: (1) scope definition, (2) selection of bibliometric analysis techniques, (3) data collection, (4) bibliometric analysis execution and, (5) evidence analysis and synthesis. Objectives, methods, relevant tools, and required analyses were identified for each phase, as illustrated in Figure 1. This process was developed within a conceptual framework subdivided into three sections: performance analysis, science mapping, and trend analysis. The performance analysis synthesized the scientific production metrics, and these metrics facilitate the identification of trends in scientific production and collaboration, which is crucial for understanding trends in sustainability and digitalization in linear projects. Science mapping contemplates the interaction between different research fields through the analysis of occurrence and co-occurrence metrics, allowing the identification and grouping of terms into clusters. These clusters are categorized as niche, motor, basic, and emerging and declining themes. Finally, trend analysis facilitates the identification of methodological and technological approaches shaping the development of sustainability and digitalization in linear projects. This study, therefore, provides a panoramic view of current trends in the field of study and lays the groundwork for future research.

3.1. Scope Definition

The scope of this study was defined by two main aims: (1) to identify the components that constitute the research field of digitalization and sustainability in linear infrastructure projects and (2) to analyze the methodological and technological trends of digitalization and sustainability in linear infrastructure projects. Therefore, this study focuses on answers to the following research questions (RQ):

RQ1: What are the development metrics for the topic of sustainability and digitalization in linear projects?

RQ2: What are the components constituting the digitalization and sustainability research fields in linear infrastructure projects?

RQ3: What are the methodological and technological trends of digitalization and sustainability applied to linear infrastructure projects?

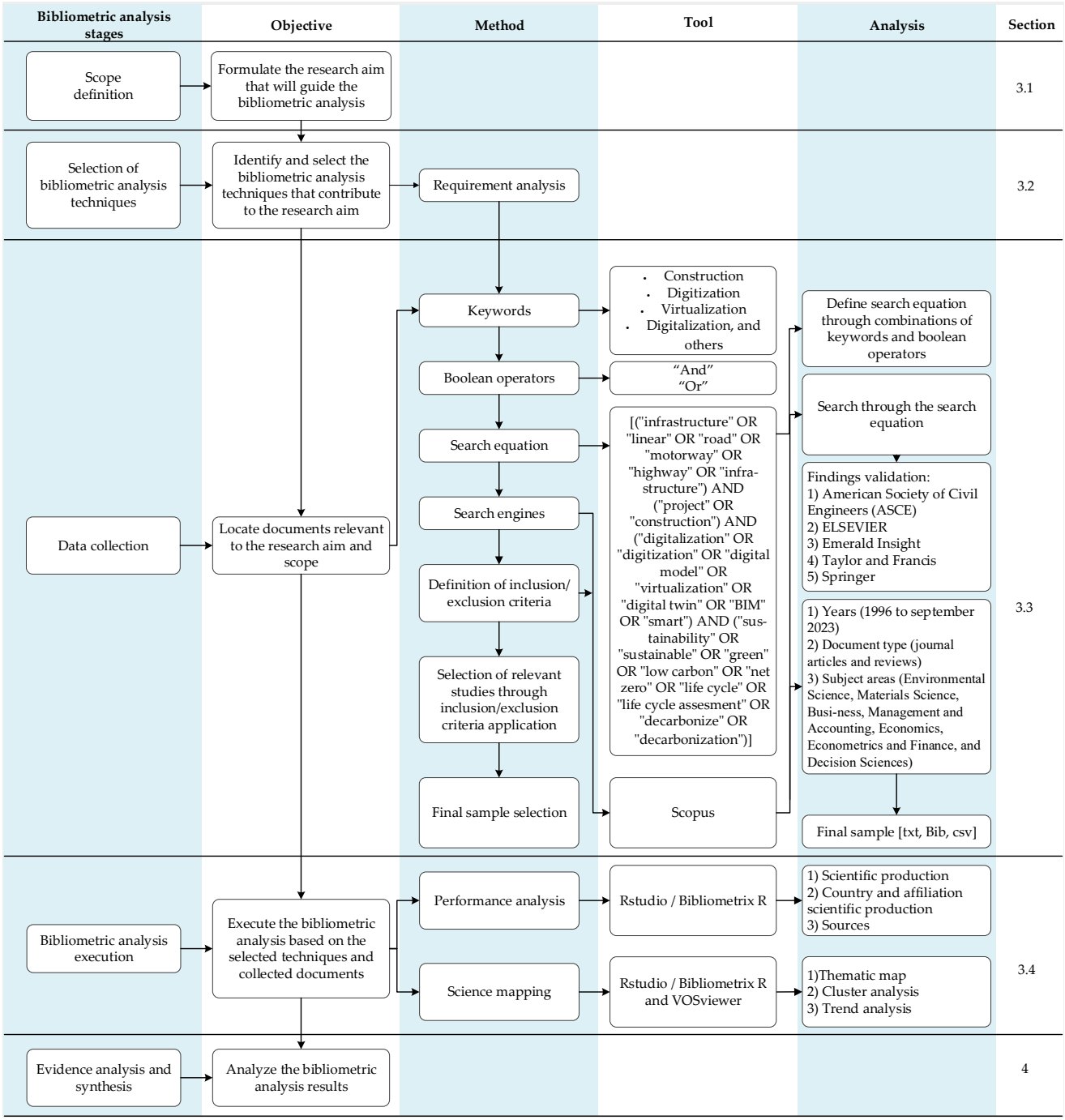


Figure 1. Bibliometric analysis methodology. An adaptation of Herrera et al. [1] and Castañeda et al. [91].

3.2. Selection of Bibliometric Analysis Techniques

The selection of techniques for the bibliometric analysis was made based on the research questions proposed. Specifically, the performance analysis was chosen to synthesize the development metrics associated with digitalization and sustainability in linear projects. For this purpose, the Bibliometrix library in the R programming environment was used. Scientific production metrics related to years of publication, authors, countries, and keywords were prioritized, given their relevance to describe the scientific production of an area of study. Consequently, the performance analysis focuses on the first research question. In parallel, the science mapping technique was used to characterize the structure of knowledge in digitalization and sustainability applied to linear infrastructure projects and emerging trends. This procedure was done through co-word analysis, creating a thematic map, and

identifying clusters and emerging trends. The cluster study provided an in-depth view of emerging trends in methodologies and technologies, which are expected to catalyze both digitalization and sustainability in linear projects. Science mapping was adopted to address the second and third research questions, and data necessary for applying it were obtained from the keywords extracted from the documents selected in the sample. The choice of bibliometric techniques was based on the intrinsic characteristics of the bibliometric analysis strategies and on the data required to answer research questions.

3.3. Data Collection

Data collection was carried out using the Scopus search engine. For this, the authors identified a set of keywords, which were integrated using Boolean operators "AND" and "OR", resulting in the search equation: [("infrastructure" OR "linear" OR "road" OR "motorway" OR "highway" OR "infrastructure") AND ("project" OR "construction") AND ("digitalization" OR "digitalization" OR "digital model" OR "virtualization" OR "digital twin" OR "BIM" OR "smart") AND ("sustainability" OR "sustainable" OR "green" OR "low carbon" OR "net zero" OR "life cycle" OR "life cycle assessment" OR "decarbonize" OR "decarbonization")]. This set of terms was determined through a workshop with five experts in sustainability, digitalization, and road projects, all with at least eight years of experience in their respective fields. During the workshop, a discussion methodology based on the verification of keywords present in databases of scientific papers relevant to the topic of study was emphasized. A Microsoft Excel spreadsheet was used to automatically generate the search equation from the keywords suggested by the experts. The initial version of this equation was tested in Scopus to verify compatibility with the existing literature. Following the comments made by the experts, the final version of the search equation was obtained.

The Scopus search engine was selected for this study, considering that it groups a wide variety of databases [99,100] that publish documents related to digitization and sustainability in linear projects. A first consultation in Scopus led to a total of 2030 documents, and with a preliminary filter selecting only scientific journal articles and reviews, considering the inherent reliability of these documents due to their peer review, the set of documents was reduced to 1028. A second filter, based on subject areas, selected documents within Engineering, Computer Science, Energy, Environmental Science, Materials Science, Business, Management and Accounting, Economics, Econometrics and Finance, and Decision Sciences, reduced the set to 973 papers. Subsequently, an Excel spreadsheet was created where five researchers independently reviewed each document's title, keywords, and abstract based on its relevance to answering the research questions. Through this process, 430 papers were agreed upon for inclusion. The documents that generated doubts among the researchers were discussed in a joint meeting to reach a consensus on their inclusion or exclusion. Finally, implementing these criteria resulted in a final sample of 419 documents (see Figure 2).

3.4. Bibliometric Analysis Execution

The bibliometric analysis used Bibliometrix in R, with a .xlsx file as the data source. Initially, performance analysis was addressed, focused on examining trends in the number of publications, collaborative networks, and scientific output by country and affiliations. This procedure aimed to identify the leading institutions and nations contributing to the development of digitalization and sustainability in linear projects and to understand their impact, scope, and temporal trends in scientific production. For scientific mapping, the frequencies of the keywords assigned in Scopus for each document in the sample were considered. This made it possible to discern the main lines of research in the field of study. From the frequencies of occurrence and co-occurrence, five clusters were highlighted that delineate the structure of knowledge in the field: (1) life cycle analysis management, (2) digitalization of linear infrastructure, (3) sustainable development, (4) road construction, and (5) road administration.

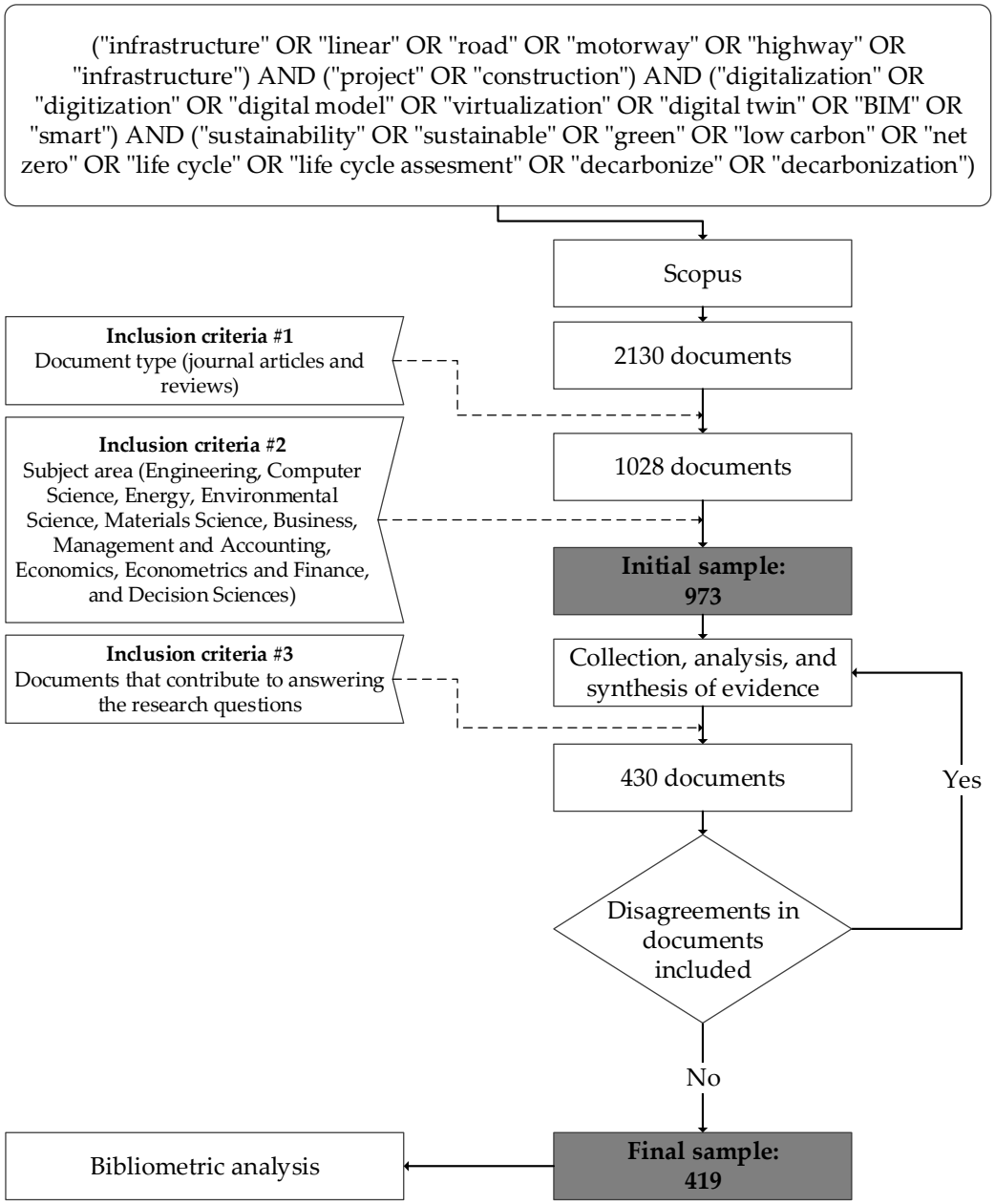


Figure 2. Document flow for sample selection.

With the clusters defined, we proceeded to a thematic map analysis, a two-dimensional graphic representation reflecting the thematic and conceptual interrelationships of the study sample. This map highlights research trends and identifies predominant and emerging thematic areas, showing their interconnection and evolution within the literary corpus analyzed. This map was elaborated considering Callon's centrality (C) and Callon's density (D) metrics (obtained in the Bibliometrix library in R by Equations (1) and (2)). The clusters were categorized into basic themes, niche themes, motor themes, and emerging and declining themes. It is essential to mention that Callon's centrality indicates how the terms in a cluster interact with each other, serving as a measure of the relevance of a topic in the field studied. Callon's density reflects the internal cohesion of a cluster, relating to the degree of development of the topic under study.

$$C = 10\sum e_{kh}, \quad (1)$$

where e_{kh} is the equivalence index, k is a keyword related to the cluster, and h is a keyword related to other clusters.

$$D = 100\sum \frac{e_{kh}}{w}, \quad (2)$$

where e_{ij} is the equivalence index, i and j are the keywords related to the cluster, and w is the number of keywords.

3.5. Evidence Analysis and Synthesis

The analysis and synthesis of the results were carried out based on performance analysis and science mapping. The performance analysis results are presented in Section 4.1, divided into (1) scientific production, (2) country scientific production, (3) network collaboration, and (4) sources. The results obtained for scientific mapping are presented in Sections 4.2 and 4.3, divided into (1) thematic map and (2) cluster analysis. Finally, Section 4.4 presents the trend analysis based on the performance analysis and science mapping findings.

4. Results

4.1. Performance Analysis

4.1.1. Scientific Production

Figure 3 displays the annual scientific document production complying with the search equation, depicting five main periods from 1996 to 2023. The years 2002, 2009, and 2011 had the highest number of publications, with a 200% variation. However, there needed to be explicit integration between sustainability and digitalization in infrastructure projects in the following years, resulting in no standard variation or tendency. Period I (1996 to 2010) is a stable period where publications regarding sustainability and digitalization integration in infrastructure are rare. The number of publications maintains an average of 0.9 publications per year, possibly explained by the Sustainable Development definition reported in the Bruntland report in 1987 [101] and the United Nations Conference on Environment and Development (UNCED) in 1992 [102], but there is no mention yet of digitalization in construction or infrastructure in public initiatives. There is a period between 2001 and 2005 where the number of publications increased, probably coinciding with the publication of the Millennium Development Goals in 2000 [103] and the initiative to start acting upon sustainability and infrastructure. The number of citations also was low, having its peak in 2004 with 16 citations.

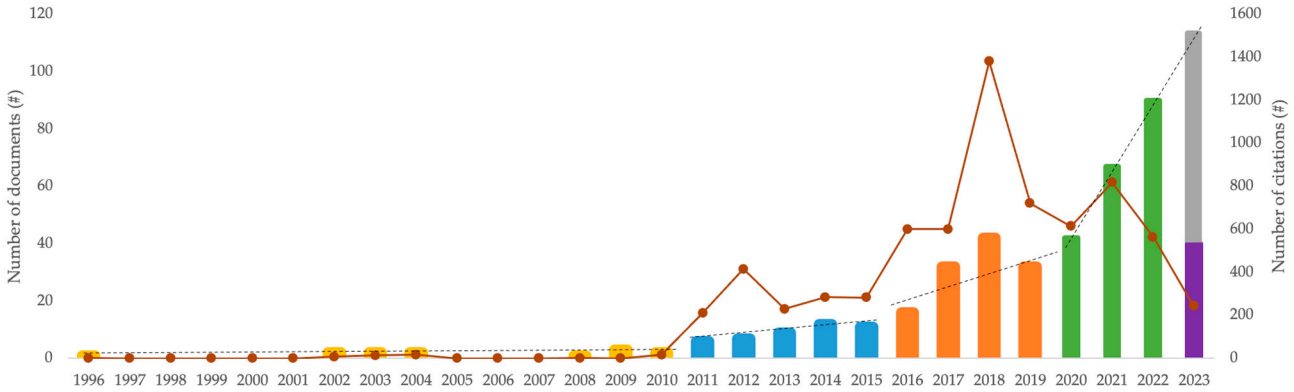
Period II (2011 to 2015) can be defined as a transition period where the number of publications starts rising. This accelerated growth can be explained by the "Industrie 4.0" publication in Germany in 2011 [104] and the public initiatives in developed countries such as the USA and UK, with their early publication of BIM standards for the construction industry (NIBS BIMC, PAS 1192). The number of citations started rising, peaking in 2012 with 415 citations.

Period III (2016 to 2019) starts defining an exponential trend in scientific production on this topic, defining a much more accelerated growth than Period II. The increasing publication of BIM standards and Sustainable Construction protocols in various countries (USA, UK, Singapore, New Zealand, Canada, China, and so on), the late influence of the "Industrie 4.0" publication explained by the average journal publications schedules (that can take up to two years since draft preparation of journal articles after the research project begins), and the relevant publication of the Sustainable Development Goals in the 2030 Agenda in 2015 [105] may explain this tendency. Period III had the highest citation peak in 2018, with 1381 citations, demonstrating a higher trend on the topic at this period.

Period IV (2020 to 2022) shows a more significant ascendant trend of sustainability and digitalization publications in linear projects, possibly explained by the ISO 19650 international standard publication in 2019 and 2020 [106] and the growing interest in the 2030 Agenda application in construction. The Construction 4.0 concept originated in this period (2020), powered by the increasing attention to Industry 4.0 technologies

application in the architecture, engineering, and construction industries and the global need for immediate action on the climate crisis [25]. The highest peak of citations can be found in 2021, but it is not higher than 2018.

Finally, 2023 documents are presented in a separate period, Period V, since the number is only part of the present study development. However, given the tendency calculated through linear regression, we project 114 documents published by the end of 2023, the most significant number of publications in digitalization and sustainability of linear infrastructure projects. Since the number of citations does not have a clear tendency, the number presented in 2023 is partial.



	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Period I (#)	1	0	0	0	0	0	2	2	2	0	0	0	1	3	2													
Period II (#)																6	7	9	12	11								
Period III (#)																					16	32	42	32				
Period IV (#)																									42	67	90	
Period V (#)																												40
Projected (#)																												114
Variation (%)						-100	200	0	0	-100	0	0	100	200	-33	200	17	29	33	-8	46	100	31	-24	31	60	34	-56
Citations (#)	2	0	0	0	0	0	7	13	16	0	0	0	1	0	17	211	415	230	285	283	601	600	1381	721	614	818	565	243

Year of publication

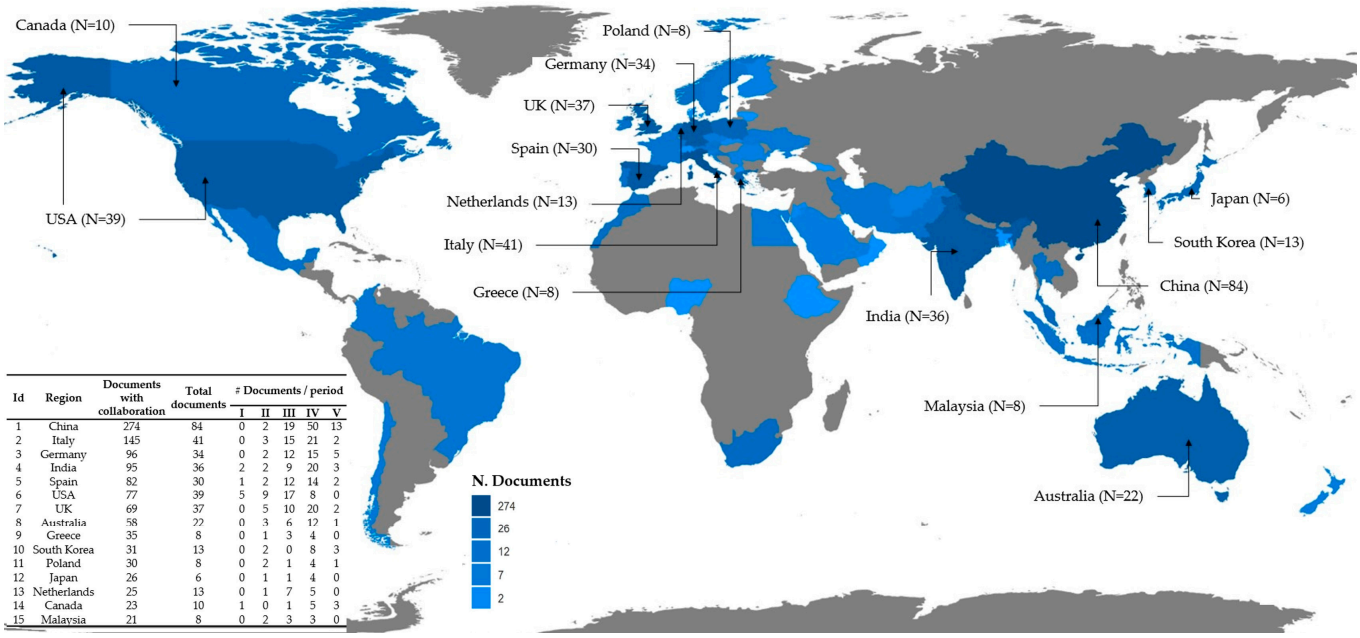
Figure 3. Scientific production per year (number of documents (#) and number of citations (#)) in digitalization and sustainability in linear projects (1996–2023). Dashed line shows the linear regression of every period tendency.

Documents with an outstanding number of citations are observed. For instance, in road projects, Abhijith et al. [107] conducted a literature review on the impact of various green road infrastructures on air quality in urban environments. Their findings indicate that trees worsen air quality in street canyons. Low, dense, tall vegetation in open roads helps reduce pollution in leeward areas. Meanwhile, in bridge projects, Kaewunruen et al. [75] applied 6D BIM models to manage the life cycle of bridge infrastructure.

The 6D BIM model integrates three-dimensional information with time scheduling, cost estimation, and carbon footprint analysis throughout the bridge project. The study reveals that some materials generate more embodied carbon emissions, but the early implementation of 6D BIM allows stakeholders to collaborate and improve sustainability and cost efficiency. In the rail projects, Häußler et al. [108] investigated the verification of code compliance in structural models of railway construction using BIM-based visual programming languages.

4.1.2. Country Scientific Production

Figure 4 shows the scientific production by country for the first 20 countries publishing about digitalization and sustainability in linear infrastructure projects. In the first five countries, it is possible to notice Asian and three European countries, followed by the leading English native speakers: The United States, the United Kingdom, and Australia. The "documents with collaboration" column is related to the co-authors' nationality, while the "total documents" column shows the nationality of the corresponding author.



Id	Region	Documents with collaboration	Total documents	# Documents / period				
				I	II	III	IV	V
1	China	274	84	0	2	19	50	13
2	Italy	145	41	0	3	15	21	2
3	Germany	96	34	0	2	12	15	5
4	India	95	36	2	2	9	20	3
5	Spain	82	30	1	2	12	14	2
6	USA	77	39	5	9	17	8	0
7	UK	69	37	0	5	10	20	2
8	Australia	58	22	0	3	6	12	1
9	Greece	35	8	0	1	3	4	0
10	South Korea	31	13	0	2	0	8	3
11	Poland	30	8	0	2	1	4	1
12	Japan	26	6	0	1	1	4	0
13	Netherlands	25	13	0	1	7	5	0
14	Canada	23	10	1	0	1	5	3
15	Malaysia	21	8	0	2	3	3	0

Figure 4. Scientific production by country.

China and India: Two of the most advanced countries in technology and digitalization. However, China is also known as a high-contaminant country, ranking as the region with the highest population, requiring immediate action and far-reaching initiatives to fulfill sustainability demands [109]. Their strong BIM initiative and sustainability goals make China a vital part of the digitalization and sustainability formula field of research. As the second most populated country in the world, India makes sustainability development a big goal on their agenda. This country also has a strong BIM initiative, especially since 2016, matching their ascendant tendency of publications from Period III.

Italy, Germany, and Spain: European Union (EU) countries can initially be studied similarly. The EU has a strategic framework for public sector BIM programs, guiding all digitalization initiatives in the construction sector of EU countries. This strong BIM public initiative, added to the significant involvement in the Agenda 2030 sustainable development goals of EU countries [110], makes the region a leader in sustainability and digitalization in the linear projects research field.

United States, United Kingdom, and Australia: Countries leading digitalization and sustainability initiatives in public administration. Although their overall scientific production ranks lower than other countries in Figure 4, they have shown a rising trend in scientific production since Period II.

On the other hand, Latin American and African countries are noticeably underrepresented in the top 15, showing low levels of research on the integration of digitalization and sustainability in linear projects. However, it is expected that the coming years will see more publications from these countries, considering the need to develop linear projects for their economic and social development.

Figure 5 shows the number of cited documents by country. China (15.6%), the US (15.3%), the UK (14.7%), Italy (12.7%), and Australia (11.9%) made significant contributions. These countries exhibit a higher volume of cited publications than the average (245) of the 20 countries analyzed. The number of citations for documents in the top five represents 70% of the total sample, highlighting the interest in these nations for research and scientific production on issues of sustainability and digitalization in linear infrastructure projects. This coincides with indices of infrastructure development and innovation in Europe, the US, and Australia, marking a significant gap with Latin American countries, which, in this analysis, are represented by Mexico, ranked 20th with 26 citations (0.5%).

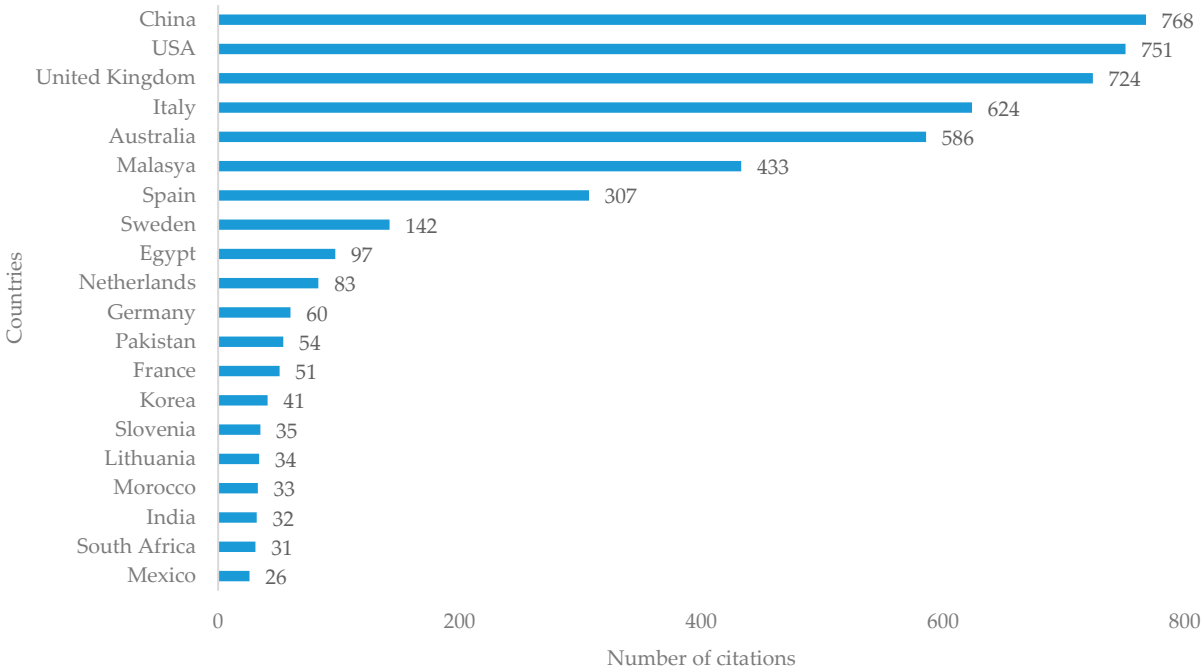


Figure 5. Number of citations by country.

4.1.3. Network Collaboration

The evaluation of the geographical affiliation of the authors in the selected sample, using the Bibliometrix library in R, reveals the existence of six main collaborative networks. Of these, three span more than ten countries (as seen in Figure 6). China figures prominently, demonstrating many collaborative papers and standing out in a network that includes the United States, United Kingdom, Australia, South Korea, and Norway, among others. In a second network, Italy and Germany lead a collaborative network that stands out for its joint work with authors from Greece, Portugal, Canada, and Denmark. In a third network, Spain and Ireland stand out, showing collaboration with authors from the Netherlands, Poland, Croatia, Macedonia, and Chile, among others. Relating the results of Figure 6 with Figure 4, a high coherence is found to the extent that the six networks with the most significant collaborative network respond to the classification of countries by scientific production.

These networks' cultural and geographic diversity enriches research processes, providing multiple perspectives that lead to multifaceted solutions applicable in different contexts. However, the limited participation of African and Latin American countries in these collaborative networks is notable. This situation could be related to these regions' limited scientific production and specific research priorities. The absence of some countries in the collaborative networks implies a limitation in the research work's diversity of perspectives and approaches. This phenomenon could result in a limited view of possible advances in sustainability and digitalization in linear projects.

4.1.4. Sources

The analysis shows that the top five journals with the highest number of papers linked to the selected sample comprise: (1) Sustainability (n = 41), (2) Bautechnik (n = 9), (3) Automation in Construction (n = 8), (4) Transportation Research Record (n = 7) and (5) Tunnelling and Underground Space Technology (n = 7) (each one). A marked dominance of Sustainability is evident. The volume of published papers is more than four times higher than that of the journal, with the second-highest number of associated documents. The significant relevance of Sustainability may be related to its multilayered approach, and this is a frame in which linear projects have considerable importance because of the generation of diverse requirements, and capture the interest of researchers and professionals in the construction sector. Bautechnik stands out in the field of construction technology,

with a particular focus on digitalization. This topic is relevant in various technological areas applicable to the construction industry. Automation in Construction is one of the scientific journals with the highest global impact in information technologies applied to design, engineering, construction, and maintenance, closely linked to the digitalization of linear projects.

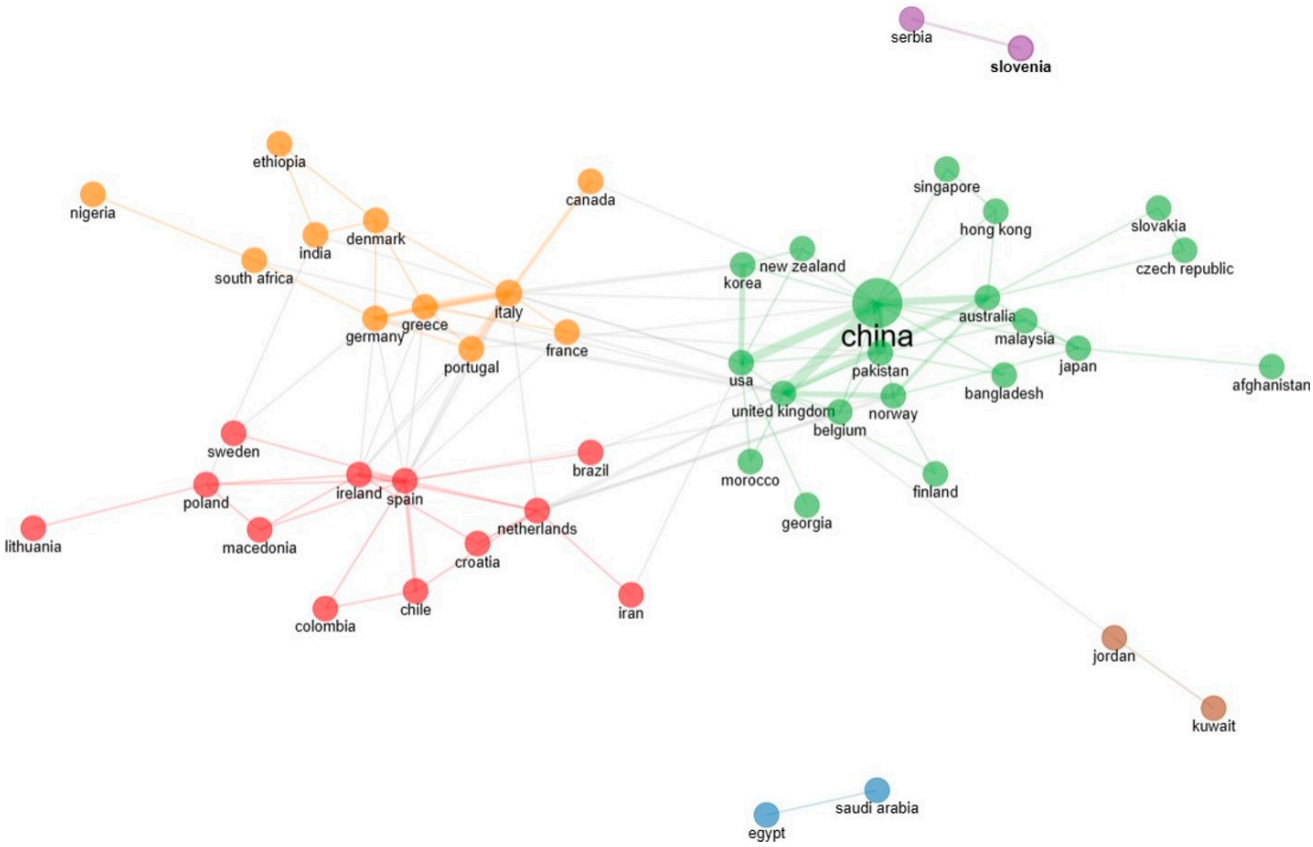


Figure 6. Inter-country collaboration networks.

An analysis of trends shows a progressive increase from 2010 in the number of publications among the twelve journals with the highest number of papers (see Figure 7). This reflects publishers' interest in addressing digitalization and sustainability in linear projects in scientific literature, as mentioned in the analysis of scientific production section. An interest aligned with global and climate challenges requires great research efforts to develop innovative solutions with a long-term vision, especially in sectors such as construction, which represents one of the economic groups with the highest consumption of resources and the highest emissions of greenhouse gases around the world. Figure 7 illustrates the trend of sources since 1996. Most sources have less than ten cumulative occurrences up to 2023. However, the Sustainability journal experienced significant growth starting in 2017, which can be related to the boost sustainability received from the formulation of the Sustainable Development Goals with the Agenda 2030 and the digitalization supported by the ISO19650 standard [106].

Sources	N° documents
Sustainability (Switzerland)	41
Bautechnik	9
Automation in Construction	8
Transportation Research Record	7
Tunnelling and Underground Space Technology	7
Applied Sciences (Switzerland)	6
Sustainable Cities and Society	6
Buildings	5
Carreteras	5
IEEE Access	5
International Journal of Construction Management	5
WIT Transactions on Ecology and the Environment	5

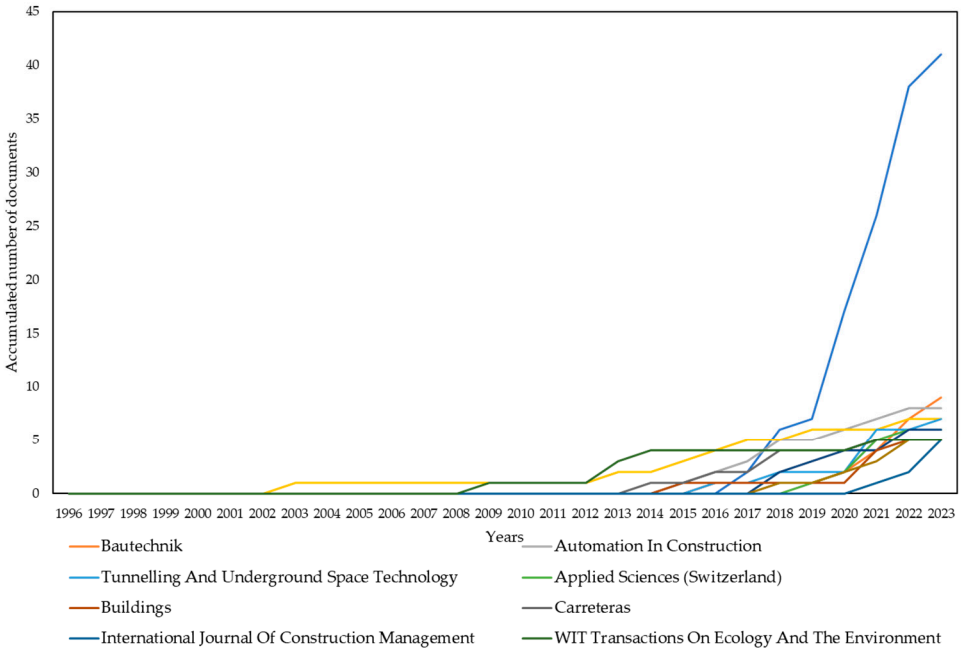


Figure 7. Number of documents by source.

4.2. Thematic Map

A thematic map is used to analyze trends and summarize information related to research topics. The map generates groups of words or clusters with high incidence and categorizes them into four quadrants based on density and centrality metrics. These quadrants are Niche themes, Motor themes, Emerging or Declining themes, and Basic or Core themes (see Figure 8). The thematic map helps to understand the internal relationship between terms within each cluster and how they are linked to the terms of other clusters. The representation of information in this way is useful for analyzing and visualizing complex data.

Grouping research terms into four quadrants provides an understanding of the development and relationships between various research topics. The first quadrant (niche themes) includes terms with low centrality and high density. These terms represent specific topics with strong internal links but little relationship to other cluster groups. The motor themes quadrant includes terms crucial for research with high centrality and high density, which indicates a strong internal relationship between the terms of the cluster and a high level of development links concerning other clusters. The third quadrant is for emerging or declining themes and is classified by low centrality and low density. This reflects low levels of development and little relationship with other research terms. These themes have yet to be widely studied because they have gained strength or lost importance over time. The fourth quadrant (basic themes) is characterized by high centrality and low density. Terms in this quadrant represent a high level of development in relation to external terms from other clusters and a high potential for development in internal links, leading the knowledge base for research development [91].

- Niche Themes: These are related to transportation, road construction, automation, and asphalt pavements and suggest an inclination towards integrating transport systems and a keen interest in enhancing the user experience. The infrastructure can be improved by incorporating materials with physical-mechanical properties to extend its useful life and enhance its quality. The focus is mainly on asphalt pavements, widely used due to their versatility and resistance as a tread cap for mineral aggregates coated and cemented with asphalt [111].

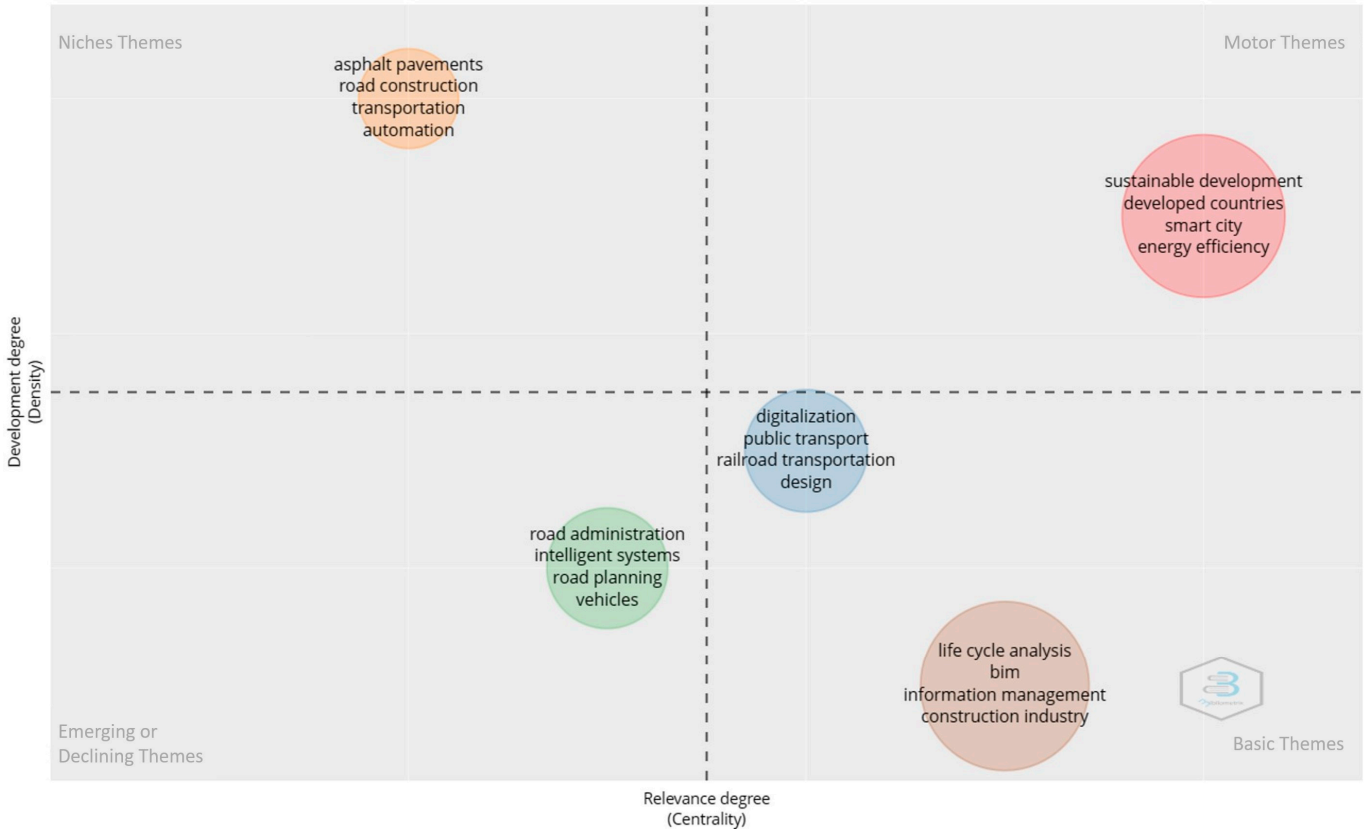


Figure 8. Linear infrastructure thematic map.

Also, research on automation tools for highway construction and transportation projects is crucial. Advancements in technology have enabled the simulation of road systems in terms of technical performance, use, and service provision. This is essential because as the population grows, the demand for better road corridors also increases, posing challenges in project planning, execution, and supervision. Technological development has become a key ally in capturing and processing data in complex contexts.

- Motor Themes: Group together terms discussed in current research within the construction sector, including construction and linear infrastructure projects. Sustainability and sustainable development have revolutionized the traditional idea of developed countries, which previously focused solely on economic growth. By incorporating sustainability into development, the emphasis shifts towards improving the population's quality of life and well-being while respecting the limits imposed by nature. Protecting natural resources is becoming increasingly important, given the critical ecological limits of climate change, biosphere integrity, land use, ocean acidification, and other global issues. This requires the involvement of various actors, including the industry, which must adapt their production processes to reduce the extraction of natural resources and minimize waste generated throughout the value chain [56].

It is crucial to address factors such as exploiting natural resources to obtain raw materials, energy consumption, impact on ecosystems due to intervention, and emissions, with a sense of urgency right from the planning stage of projects. One relevant trend is energy efficiency studies, which can help reduce greenhouse gas emissions and contribute to mitigating climate change. Additionally, energy efficiency studies can generate significant savings in the long term, considering that the construction sector is one of the largest energy consumers worldwide. Together with the transport sector, it is responsible for over 30% of final energy consumption and almost 40% of carbon dioxide (CO_2) emissions, according to the International Energy Agency (IEA) [112].

The term "smart cities" is also important in motor themes research. It helps to tackle the complexity of linear infrastructure projects [85] by leveraging information and communication technologies such as big data, analysis tools, and computer simulations. These technologies aid decision-making and enable efficient and sustainable project management throughout all life cycle stages. This includes urban planning, automation control, mobility and transport, solid waste management, efficient operation, and low emissions.

- Emerging and Declining Themes: Fields of road planning, road administration, intelligent systems, and vehicles are gaining significance. The number of publications in these areas has been steadily increasing. While some of these topics have been studied and developed for a long time in the building sector, they have yet to be given due attention in the linear infrastructure sector. This suggests that the number of investigations will continue to increase in the short and medium term, reinforcing the belief that these are emerging issues. When comparing the building sector with the linear infrastructure sector, the latter must adapt methods, techniques, and technological tools to enhance buildings' performance. For instance, several variables must be considered in planning linear projects to address their complexity. Tools that help analyze restrictions, limitations, resource allocation, optimization, linking of actors, simulation of construction processes, variation of climatic conditions, etc., can be extremely useful in this context [113].

Intelligent systems play a crucial role in the planning and administration of linear projects, ensuring that transport services are provided with adequate security measures. As these issues continue to emerge, we expect the study and implementation of approaches related to artificial intelligence, the Internet of Things, and intelligent and innovative materials that can mitigate negative impacts and enhance the resilience of projects in the face of climate change to improve significantly.

- Basic Themes: This quadrant reveals two groups: one relates to digitalization, public transport, road transport, and design, while the other is connected to life cycle analysis, BIM, information management, and construction. These groups represent the center of current research seeking to relate digitalization as a tool for the design, planning, execution, and maintenance of sustainable linear infrastructure projects. The trend of using digital models and information management strategies aims to improve understanding and connection between different project actors, ultimately favoring the decision-making process. Linear road transportation projects require integrated management considering multidisciplinary factors throughout their life cycle. Therefore, digitalization and the possibilities of visualizing the proposed designs with constructive reality contribute to reducing risks, optimizing resources, and overall better results.

4.3. Cluster Analysis

The words used in co-word analysis are typically taken from "author keywords" or "keywords index". However, significant terms can also be extracted from "article titles", "abstracts", and "full texts" in the absence of such keywords [98].

Therefore, this technique was chosen to identify the main themes in the research on trends in digitalization and sustainability of linear projects. Figure 9 shows the overall map, where each node represents a keyword, and the node size indicates the frequency of occurrence of a keyword. The link between nodes represents the relationship between two keywords [114]. Five main groups were defined according to the connections between the most relevant terms and words: (1) life cycle analysis management, (2) digitalization of linear infrastructure, (3) sustainable development, (4) road construction, and (5) road administration.

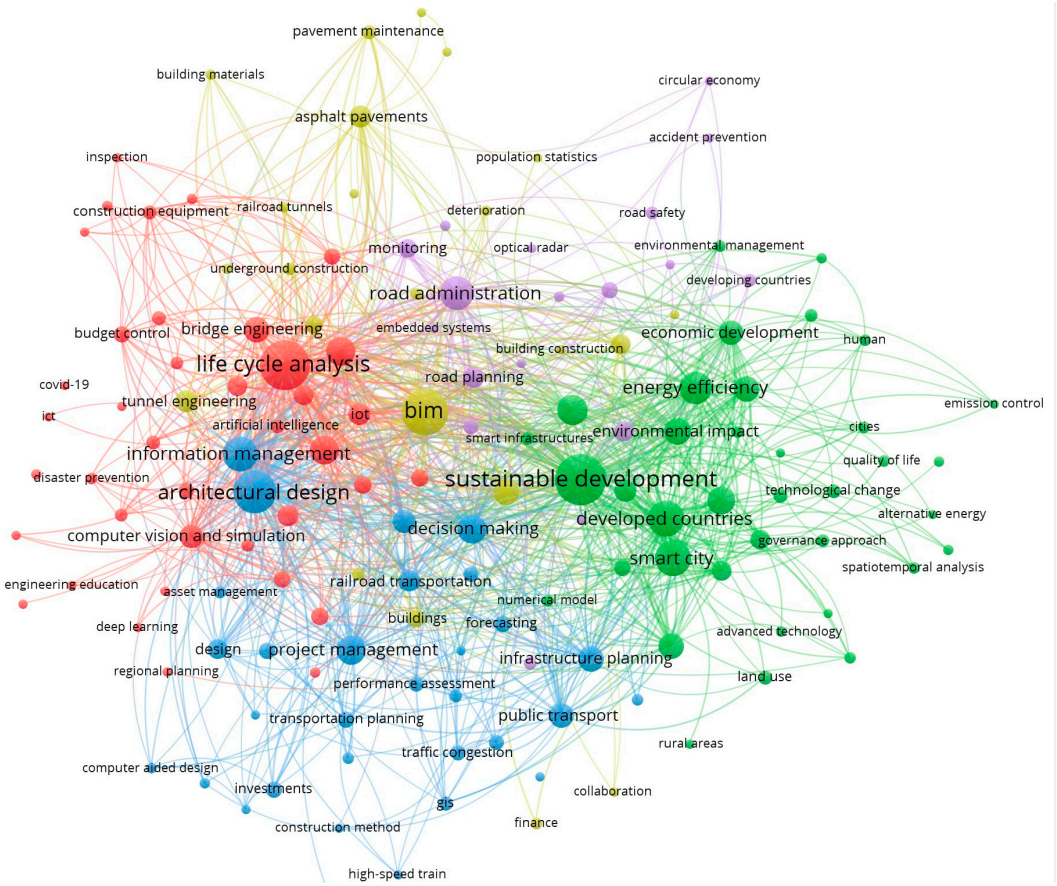


Figure 9. Cluster analysis general map.

4.3.1. Life Cycle Analysis

From the thematic map, the "life cycle analysis" cluster is one of the basic themes, including construction project stages, Industry 4.0 technologies, data analysis related to research fields, and specific linear project types (see Figures 10 and 11). The cluster is closely related to different construction project stages, particularly linear projects: maintenance, budget control, cost analysis, road construction, and structural design. It is noticeable that this cluster has a trend toward cost analysis and maintenance. The technologies associated with life cycle analysis in linear projects include ML, data integration, intelligent systems, sensors, robotics, and 3D modeling. Life cycle analysis is linked to disaster prevention, multi-objective optimization, and industrial research. Lastly, it includes specific linear project types such as tunnel engineering, bridge engineering, asphalt pavements, and roads.

This cluster is closely related to the terms of the other clusters, and its integration with BIM and sustainable development facilitates sustainability indicators in infrastructure projects [115]. Several studies have analyzed these concepts, such as Patel et al. [23] proposing a methodological framework based on the life cycle to assess the sustainability of road construction using BIM. Oreto et al. [116] describe a dynamic tool that integrates life cycle assessment (LCA) and BIM for designing asphalt pavements, automating environmental impact calculation, and considering alternative materials and recycling technologies. The frequency of "life cycle analysis" has increased since 2019, followed by BIM, as more professionals and organizations began to use BIM as a comprehensive tool for project planning, design, and management. This cluster is closely related to the terms of the other clusters, and its integration with BIM and sustainable development facilitates sustainability indicators in infrastructure projects (see Figure 10) [115].

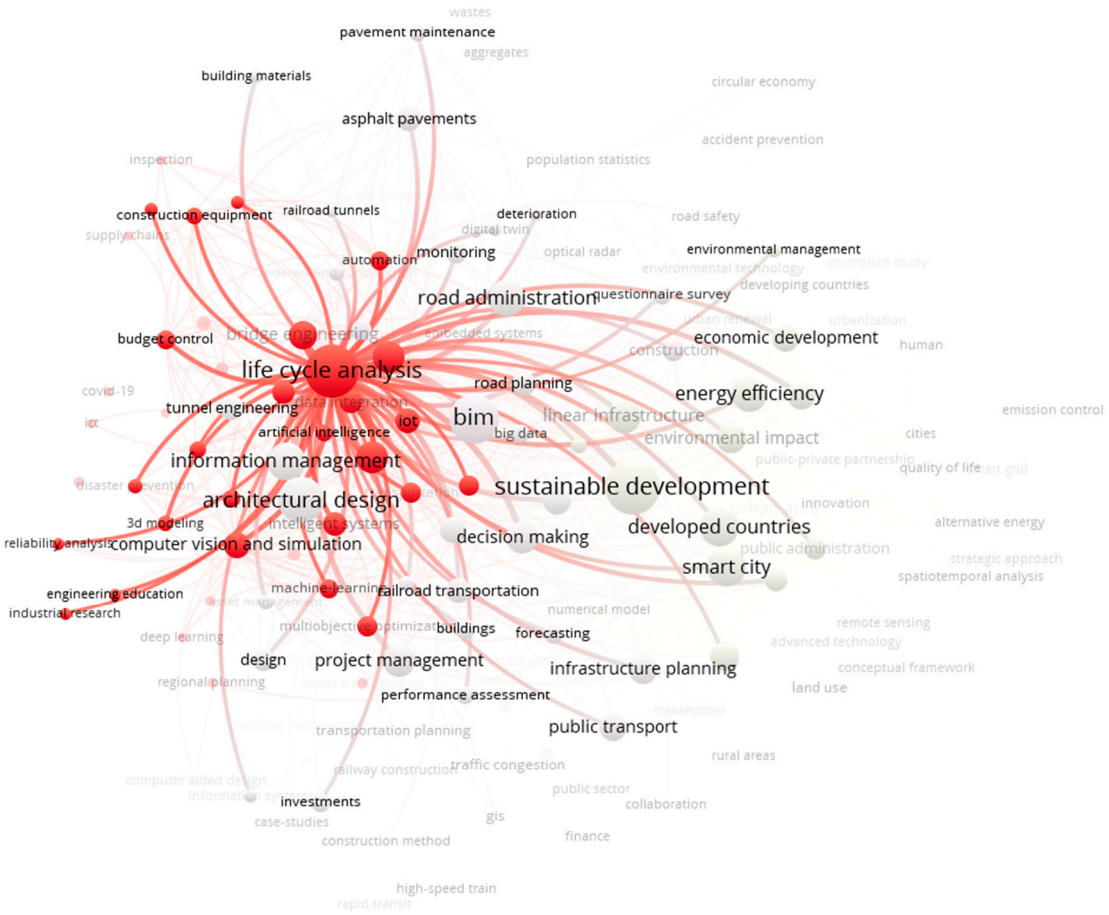


Figure 10. Internal and external relationships of the life cycle analysis cluster.

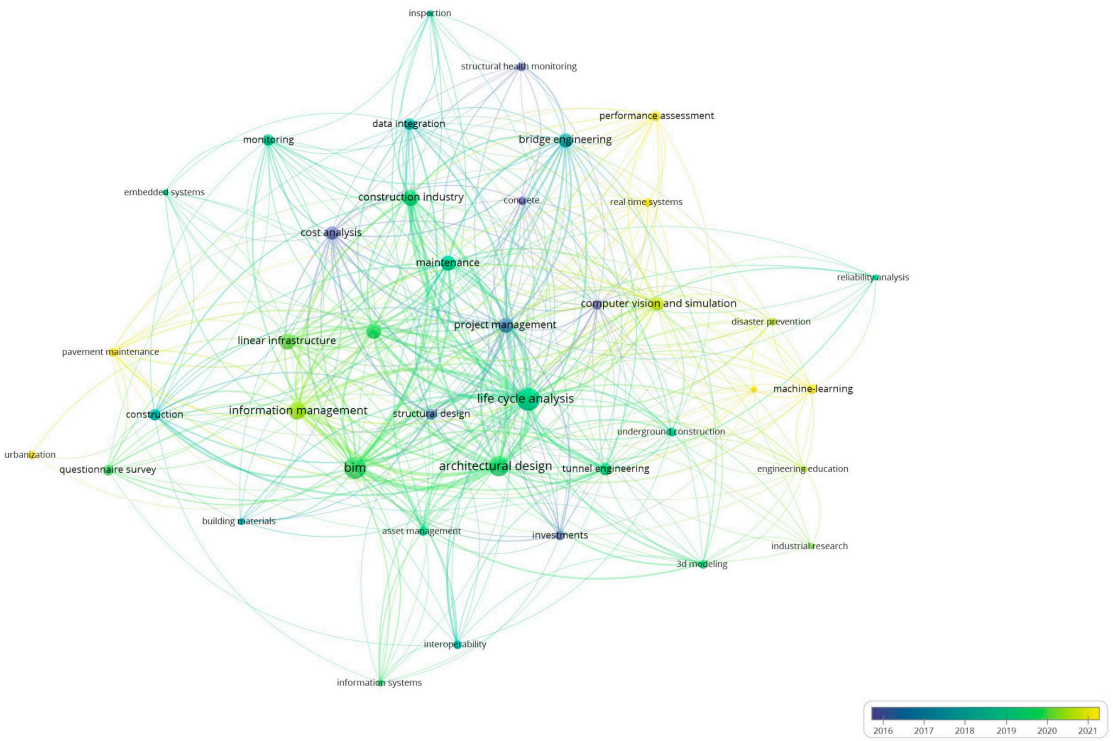


Figure 11. Terms associated with the Life Cycle Analysis cluster.

Overall, the "Life cycle analysis management" cluster shows the synergy between digitalization and sustainability and demonstrates how life cycle analysis can effectively guide decision-making, resource optimization, and long-term resilience when integrated with innovative approaches like BIM and advanced analytics. This integration fosters efficient resource management, minimizes environmental impact, and promotes a circular economy.

4.3.2. Digitalization of Linear Infrastructure

Figures 12 and 13 display the "digitalization of linear infrastructure" cluster, where BIM is one of the most used terms. The BIM methodology catalyzes digitalization in the construction industry, stimulating technological change and serving as a pillar of the digital ecosystem by integrating people, processes, and technology through digital platforms that promote project interoperability. Although BIM has been more developed in buildings, the cluster shows studies focused on digitalization in linear projects such as bridge engineering, pavement maintenance, asphalt pavements, and railroad transportation. In Figure 13, internal cluster terms such as design, construction method, health monitoring, risk assessment, and facility management are associated. It is observed that the concept of digitalization has been increasingly discussed since 2020, as well as the terms "railroad transportation" and "railway construction."

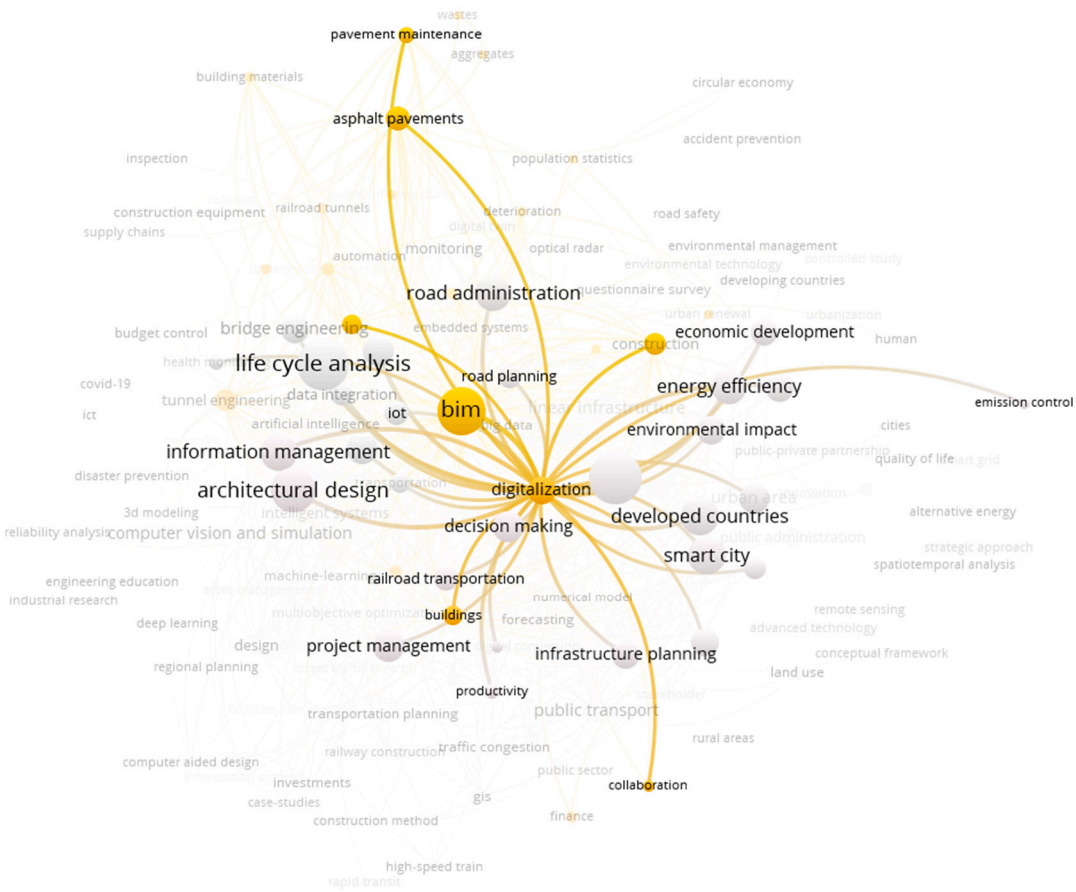


Figure 12. Internal and external relationships of the Digitalization of Linear Infrastructure cluster.

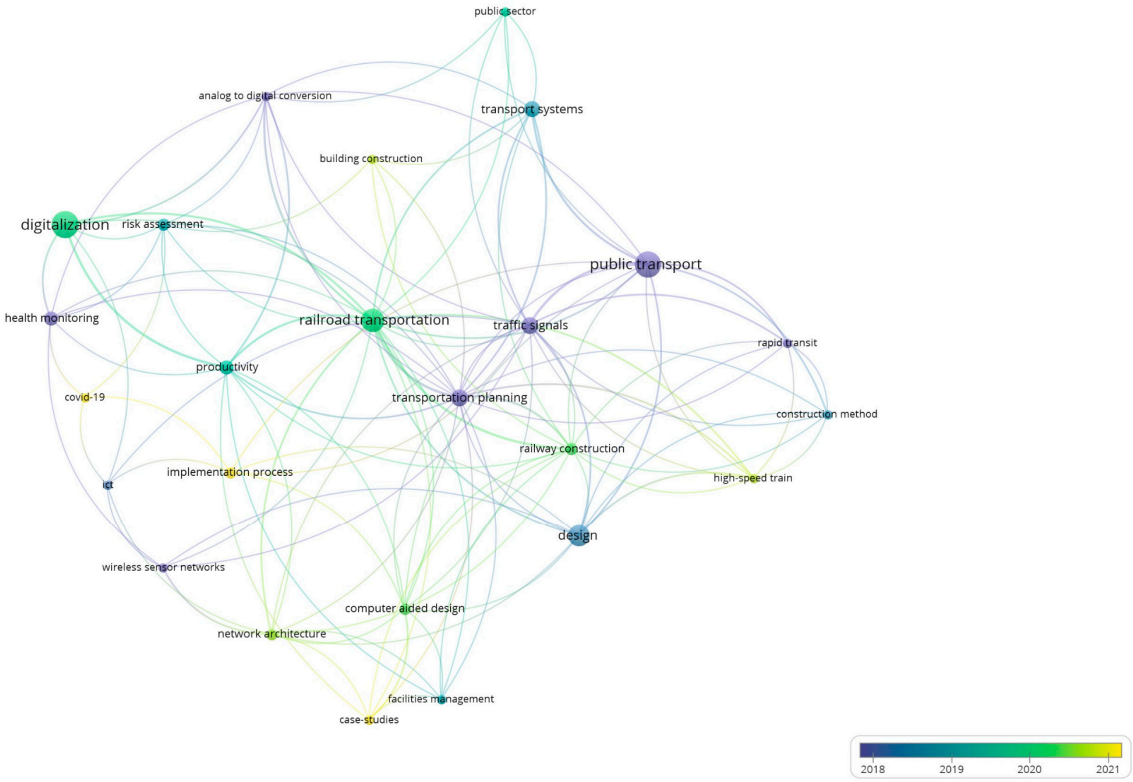


Figure 13. Terms associated with the Digitalization of Linear Infrastructure cluster.

Collaboration and Industry 4.0 tech are shown to advance sector-related Sustainable Development Goals (SDGs) in the post-pandemic era. The link between digitization and sustainability in infrastructure projects is growing stronger. This connection arises from the need to address environmental and social challenges inherent in infrastructure initiatives while leveraging technological opportunities to enhance efficiency and effectiveness. The COVID-19 pandemic accelerated this trend, driving increased adoption of digital solutions in project management and development. Implementing digital tools for communication, remote monitoring, and agile adaptation to changing conditions was promoted to ensure operational continuity amidst mobility restrictions and social distancing [117].

Cluster shows that BIM methodology is closely related to the entire lifecycle, from design to maintenance, and the relationship with sustainability, which is fundamental at all project stages. Integrating sustainability and digitalization within linear infrastructure projects presents a transformative synergy, and this fusion becomes evident as it intertwines concepts such as energy efficiency, environmental impact, developed countries, and smart cities. BIM's capacity to span the entire lifecycle of projects enhances collaboration, information management, and decision-making. This synergy optimizes operational efficiency and deepens the relationship with sustainability by addressing environmental, social, and economic impacts at every stage.

4.3.3. Sustainable Development

According to the thematic map, the "sustainable development" cluster is classified as a motor theme, and the terms compiled here guide the execution of linear infrastructure projects in an ever-changing context of climate change challenges (see Figures 14 and 15). Relevant terms such as land use, growth, urban planning, and smart cities stand out. The linkages between project management and sustainability show that literature recognizes the need to design and build projects that respect nature's boundaries. Tools that facilitate the implementation of sustainable and efficient practices are being studied worldwide. Many of these practices have emerged from other knowledge areas and have begun to be incorporated into the construction sector. An example is the circular economy, which closes

the circle of construction concepts, optimizes manufacturing and transformation processes of raw materials, reduces waste or reuse, and incorporates recycled raw materials into the value chain.

The cluster is also associated with terms such as energy efficiency and multi-objective optimization in infrastructure planning, aiming to reduce the environmental impact of road works in the context of growing concern for climate change. Proper planning allows for identifying solutions that maximize energy efficiency, integrating data and advanced technologies such as Geographic Information Systems (GIS). Sustainable transportation and traffic control are also concepts related to this cluster. Promoting public transportation and using technologies like real-time data-based traffic control and big data analysis enables efficient traffic flow management and optimization of existing infrastructure capacity. Additionally, the Internet of Things (IoT) and computer simulation provide real-time information for informed decision-making and effective urban mobility management. Information management plays a crucial role in collecting, analyzing, and utilizing relevant data, driving sustainable transportation solutions that reduce traffic congestion and improve the city's quality of life.

Apart from the strong internal relationship among terms within the cluster, there is also a robust linkage with other clusters. Figure 14 shows a significant connection with the life cycle analysis cluster, linear infrastructure digitalization, and road administration. Research has been conducted on the issue of green infrastructure in response to global warming, the shortage of energy resources, and environmental degradation. Efforts are being made to build sustainable and low-carbon infrastructures [118]. Rooshdi et al. [119] propose the integration of BIM into sustainable design for green highway construction. Moreover, Shi and Lv [120] explore the complementary advantages of integrating BIM and GIS in green highway design, construction, and maintenance. BIM is strongly linked to enhancing sustainability, as shown by Sun and Park [121], where the authors investigated the implementation of BIM for the calculation of CO_2 emissions during the construction process of a tunnel.

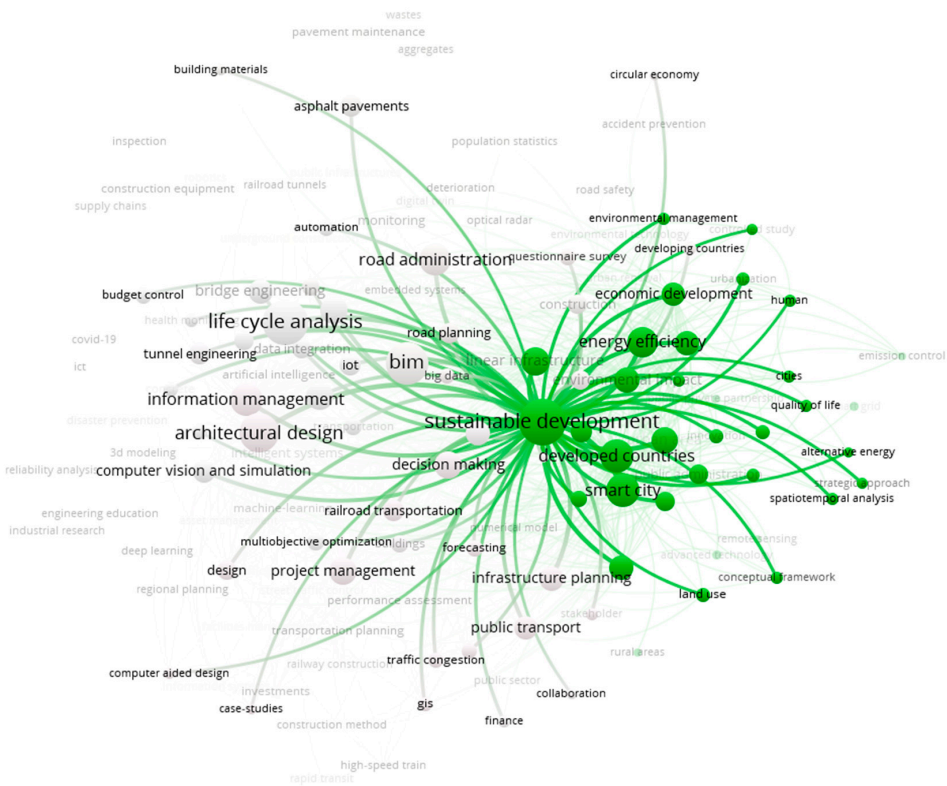


Figure 14. Internal and external relationships of the Sustainable Development cluster.

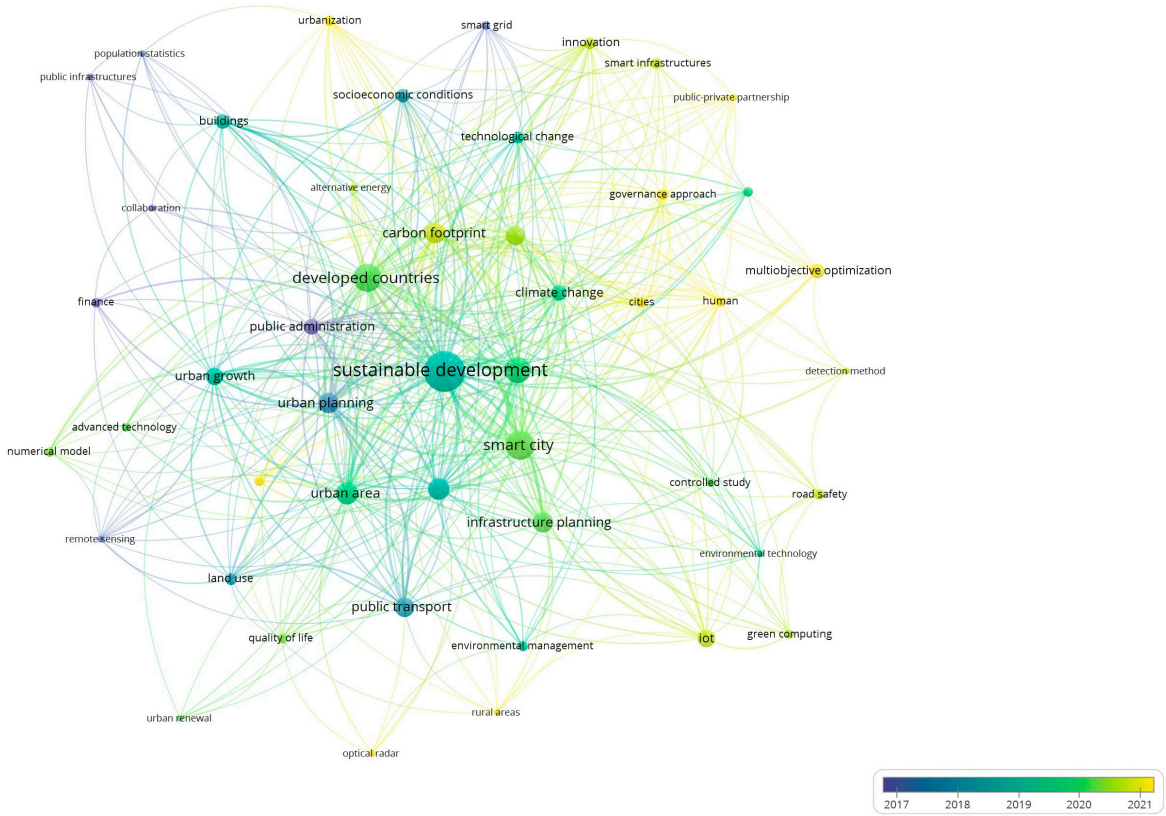


Figure 15. Terms associated with the Sustainable Development cluster.

4.3.4. Road Construction

The "road construction" cluster, comprising terms like maintenance, transportation, automation, budget control, asphalt pavements, and construction equipment (see Figures 16 and 17), is classified as a niche topic on the thematic map (see Figure 8). It exhibits strong internal cohesion due to its specialized focus. However, it has limited connections with other clusters, as niche topics tend to remain distinct within their specific domains, resulting in relatively independent relationships with broader subject areas covered by other clusters.

Regarding the digitalization of road construction, Figure 17 shows the temporal frequency of discussions around specific terms. The graph starts in 2014 with sensors, followed by robotics in 2016, automation more prevalently in 2018, and artificial intelligence gaining prominence in 2020. Recent studies have focused on the intersection of road construction and automation. An example is the SmartSite project showcased by Kuenzel et al. [122]. This initiative uses machine learning, decision theory, and distributed artificial intelligence to develop a multi-agent system tailored for road construction. The focus is on integrating detection and communication technologies to automate the real-time exchange of information within the supply chain. It introduces a real-time route planning system for compactors, significantly improving construction quality, pavement durability, and overall operational efficiency. Similarly, Maksimychev et al. [123] introduce an advanced automated system to refine control and amplify production in road construction endeavors. The system integrates real-time machinery control and dispatch systems, precisely fine-tuning machine movements and positions. The objective is to identify optimal algorithms and technologies that underscore industry automation.

With a focus on sustainability, Marzouk et al. [124] advocate a methodology grounded in BIM to evaluate the environmental impact of road construction projects. The evaluation includes a variety of indicators, such as greenhouse gases, eutrophication, acidification, and human health. The model encompasses the entire project lifecycle, offering a comprehensive pre-execution assessment tool.

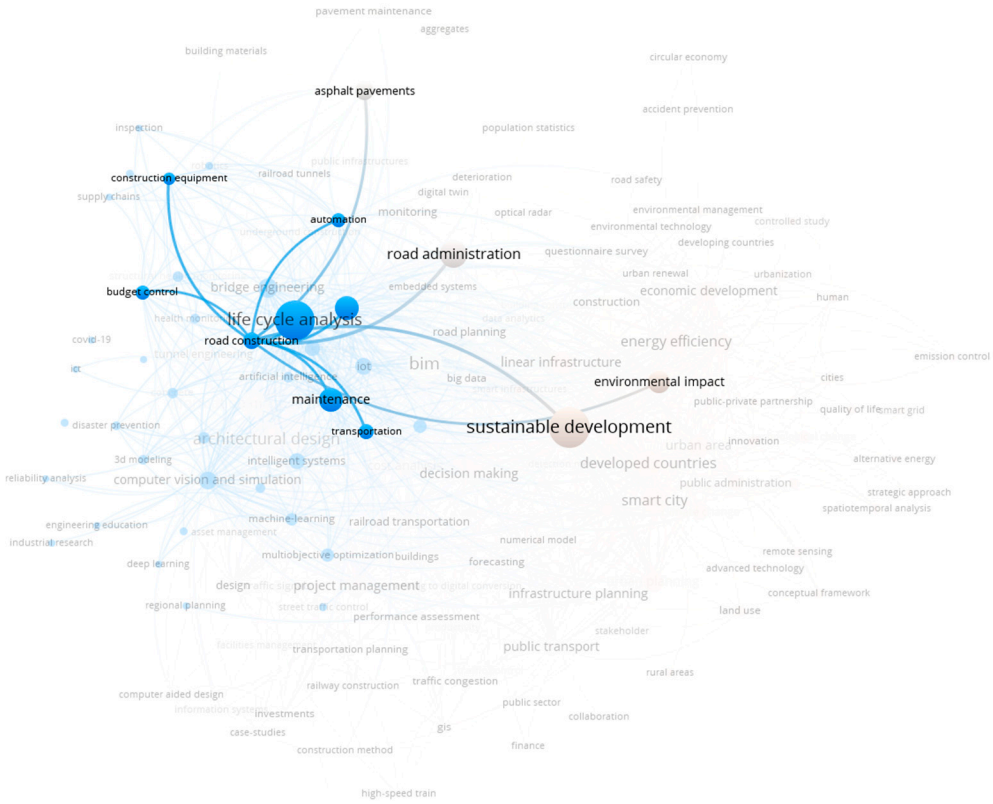


Figure 16. Internal and external relationships of the Road Construction cluster.

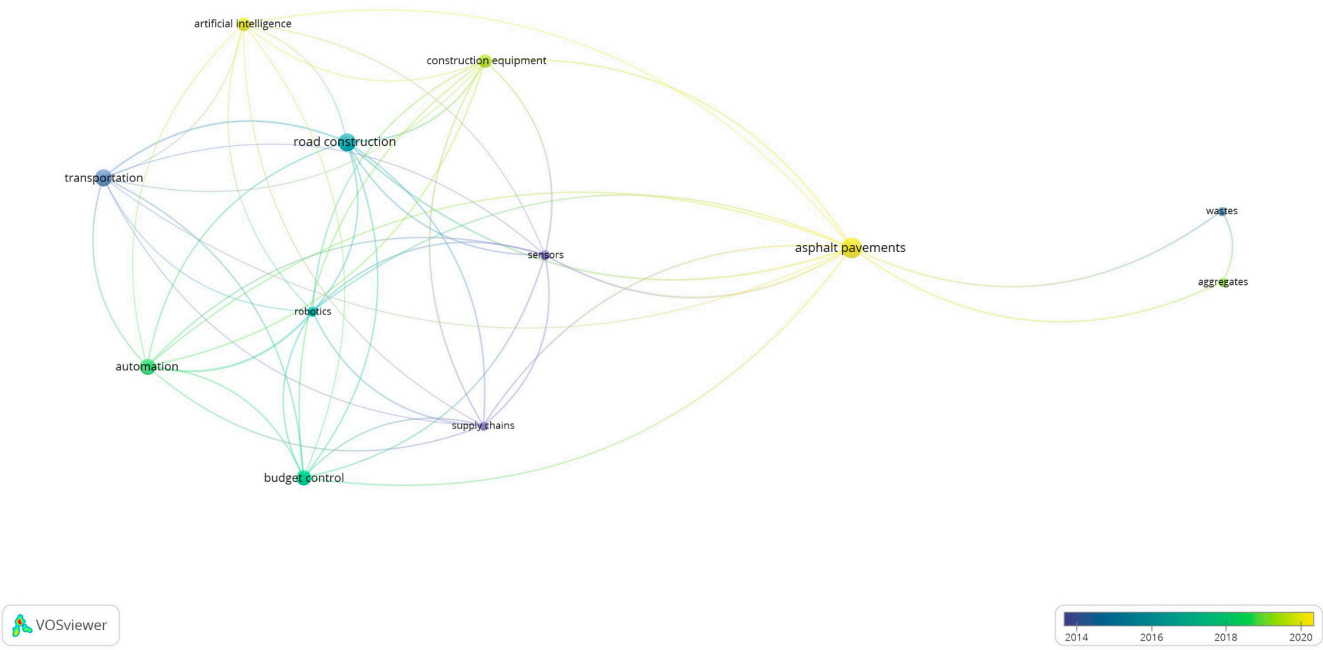


Figure 17. Terms associated with the Road Construction cluster.

4.3.5. Road Administration

The thematic map shows that the "road administration" cluster is an emerging and declining theme. Emerging themes represent growth areas in the field of road administration, while declining themes have lost relevance as the field progresses (see Figure 18). The cluster includes terms related to managing road infrastructure during operation, such as road maintenance activities, accident prevention, forecasting, deterioration, vehicular traffic

control, and sustainable mobility (see Figure 19). From 2019, terms such as intelligent vehicle highway system, big data, and air quality increased. From 2020 to 2021, the frequency of terms such as data analytics, intelligent systems, Geographic Information System (GIS), and circular economy increased. Other emerging terms from different clusters related to road administration include life cycle analysis, information management, BIM, and sustainable development. Digitalization and sustainability have transformed the management of road operations. Digitalization has revolutionized vehicle traffic control, providing innovative solutions to optimize road flow and safety.

Collecting real-time information on traffic, driving patterns, and road incidents is possible using advanced sensors, cameras, and data analysis systems. This data is processed and used to make informed decisions such as traffic light regulation, lane management, and route detours to reduce congestion and travel times [32]. Additionally, digitalization allows the implementation of vehicle-infrastructure communication systems, which facilitate interaction between vehicles and road infrastructure, improving safety and enabling a faster response to emergencies or risk situations.

Sustainability has also become a fundamental aspect of road operation management. Measures are being implemented to reduce roads' environmental footprint, such as using sustainable materials in road construction and maintenance and promoting electric vehicles and public transportation. Furthermore, renewable energy projects are being developed to power road lighting and signaling systems, reducing dependence on fossil fuels.

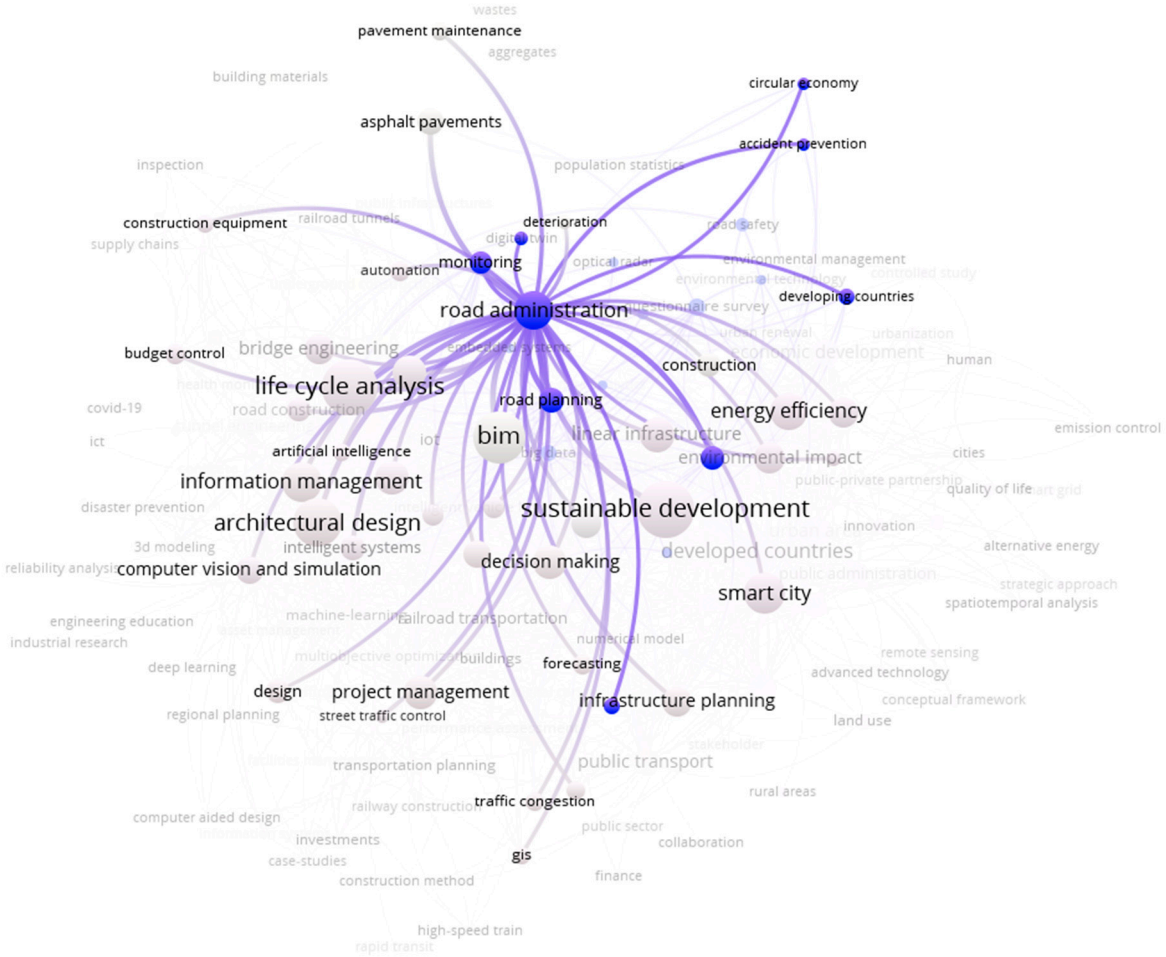


Figure 18. Internal and external relationships of the Road Administration cluster.

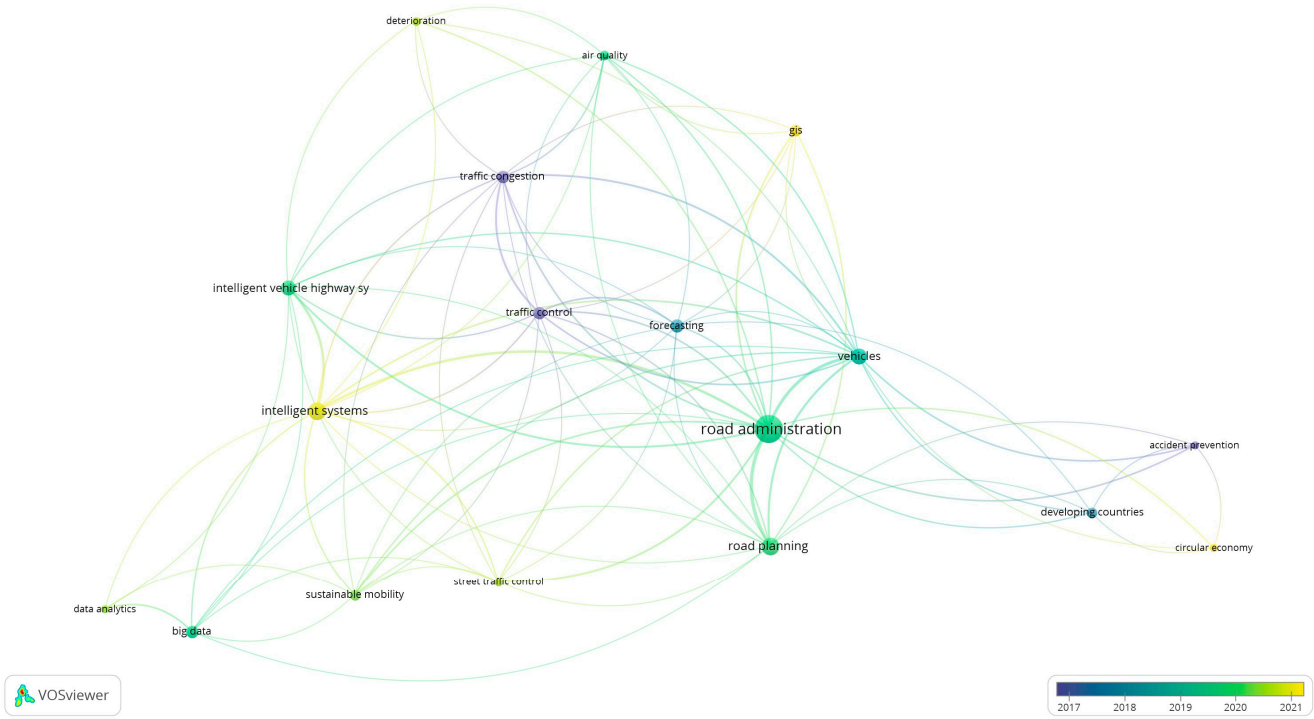


Figure 19. Terms associated with the Road Administration cluster.

4.4. Trend Analysis

Table 2 displays the frequencies of co-occurrence between digitalization and sustainability trends and the fields of work related to linear projects.

Likewise, details of these trends and their internal classification are presented below.

4.4.1. Trends in Digitalization

According to Forcael E. et al. [37]:

- Big Data: The "Urban planning" field shows a growing interest in Big Data, with 29 mentions (see Table 2). This indicates a preference for utilizing large datasets to optimize linear projects such as roads and tunnels in urban areas. In "Project management," with 25 mentions, it is likely that massive data are being used to monitor and improve efficiency in the construction of roads, bridges, and railways. However, the low presence in areas such as "Materials" suggests a missed opportunity, particularly when considering the complexities and variables of linear projects.

Internal classification: Big data, Data analytics, Data integration, Information systems.

- Technologies in Computer-Aided Design: Computer-aided design tools are becoming increasingly crucial in linear construction projects such as bridges, roads, and tunnels. The importance of these tools is reflected in the 147 mentions in "Project Management" and 99 mentions in "Design." These technologies provide the ability to model, simulate, and optimize structures before construction, which can be particularly valuable in constructing railways and complex roadways.

Internal classification: 3D modeling, BIM, Collaboration, Computer-aided design, Computer vision and simulation, Digitalization, GIS.

- Internet of Things (IoT): The IoT is increasingly used to connect devices and improve the planning and operation of roads, railways, tunnels, and bridges. This is evident from the 32 mentions in areas such as "Project Management," "Urban Planning", and "Operation". Using sensors and interconnected devices facilitates real-time monitoring and quick responses to issues in these linear projects.

Internal classification: Digital twin, Embedded systems, Intelligent vehicle highway systems, IoT, Optical radar, Remote sensing, Sensors, and Wireless sensor networks.

- Artificial Intelligence and Robotics: A field becoming increasingly prominent in "Infrastructure Projects," as evidenced by the 31 mentions in recent reports. This suggests a potential revolution in how linear projects, such as bridges, roads, and tunnels, are approached. In the coming years, we may see more automation in constructing and maintaining bridges and implementing intelligent monitoring systems on roads and tunnels.

Internal classification: Artificial intelligence, Automation, Deep learning, Machine-learning, and Robotics.

- Innovation: This trend is essential in the construction and maintenance of railways, tracks, tunnels, and bridges, which is crucial to ensure efficiency and safety. While areas such as "Urban Planning" and "Project Management" are adopting innovative approaches, it is essential to drive innovation in areas such as "Materials" and "Construction and Control" to overcome the specific challenges of these linear projects.

Internal classification: Advanced technology, Analog to digital conversion, ICT, Innovation, Intelligent systems, Real time systems, and Technological change.

Table 2. Frequency of co-occurrence between sustainability and digitization trends versus fields of work.

Fields of Work / Digitalization and Sustainability Trends	Design	Project Management	Urban Planning	Infrastructure Projects	Materials	Operation	Construction and Control	Accident Prevention and Risk Analysis	Total
Digitalization									
Big Data	14	25	29	24	2	15	3	3	115
Technologies in Computer-Aided Design	99	147	83	94	16	64	11	9	523
Internet of Things	10	32	32	21	9	32	7	4	147
Artificial Intelligence and Robotics	16	15	18	31	10	14	10	6	120
Innovation	11	34	33	33	1	23	2	3	140
Sustainability									
Sustainable development	37	76	116	68	11	47	2	8	365
Life Cycle Analysis	66	111	45	85	12	43	12	9	383
Emission Control	10	29	30	11	6	22	0	1	109
Technologies in Sustainability	6	23	37	23	4	18	1	5	117
Total	**269**	**492**	**423**	**390**	**71**	**278**	**48**	**48**	2019

Note: A darker shade of green color represents a higher frequency of co-occurrence. Likewise, a lighter shade of green represents a lower frequency of co-occurrence.

4.4.2. Trends in Sustainability

- Sustainable Development: This field shows a significant projection in "Urban Planning" with 116 mentions (see Table 2). A result suggests that when planning and designing linear projects like urban roads, bridges, and tunnels, it is crucial to prioritize sustainability. The mention of "Project Management" 76 times indicates a commitment to sustainability, particularly in linear projects such as railways and roads. However, the lower count of two mentions in the "Construction and Control" area and only eight mentions in "Accident Prevention and Risk Analysis" highlight the need for a more robust approach in these fields.

Internal classification: Circular economy, Climate change, Environmental impact, Environmental management, and Sustainable development.

- Life Cycle Analysis: A field that has been identified as a crucial trend in "Project Management" and "Infrastructure Projects," with 111 and 85 mentions, respectively. This trend highlights a growing focus on evaluating the sustainable impact of structures, including bridges, roads, and tunnels, throughout their service life. However, the life cycle analysis only features 45 mentions in "Urban Planning," indicating the need to further integrate this approach in urban planning.

Internal classification: Life cycle analysis, Multi-objective optimization, Performance assessment, Reliability analysis, and Spatiotemporal analysis.

- Emission Control: The fields "Project Management" and "Urban Planning" have been mentioned 29 and 30 times, respectively, about emissions control. This indicates a growing awareness of the environmental impact of linear projects. However, the term "Construction and Control" has no mention in the table, highlighting an area that needs special attention, particularly in projects like tunnels where emission control is crucial.

Internal classification: Air quality, carbon footprint, emission control, sustainable mobility, and wastes.

- Technologies in Sustainability: "Urban Planning" was mentioned 37 times in connection with sustainability technologies, indicating a trend toward modernization in planning linear projects. However, there were only four mentions of "Materials" and one mention of "Construction and Control," suggesting that there is still untapped potential for incorporating technological innovations in these fields.

Internal classification: Alternative energy, energy efficiency, environmental technology, green computing, and numerical model.

4.4.3. Trends in the Integration of Sustainability and Digitalization

Table 3 shows the frequencies of co-occurrence between the digitalization and sustainability trends. The combination of digitalization and sustainability has led to a surge in linear projects, as indicated by the numerous mentions in scientific articles. Computer-aided design (CAD) technologies are among the most prominent findings about sustainability trends, with a high co-occurrence with sustainable development (a value of 74) and life cycle analysis (a value of 84). This suggests that CAD tools such as BIM, GIS, and computer vision are crucial in planning and evaluating sustainable linear projects. Other digitalization trends, such as Big Data and the Internet of Things (IoT), have a noteworthy relationship with sustainable development, with values of 15 and 19, respectively. However, it is interesting to note that despite their revolutionary impact in other areas, artificial intelligence and robotics have a relatively low co-occurrence compared to sustainability trends in linear projects.

Table 3. Frequency of co-occurrence between sustainability and digitization trends.

Sustainability Trends / Digitalization Trends	Sustainable Development	Life Cycle Analysis	Emission Control	Technologies in Sustainability	Total
Big Data	15	17	3	9	**44**
Technologies in computer-aided design	74	84	24	27	**209**
Internet of Things	19	17	3	16	**55**
Artificial Intelligence and Robotics	12	19	2	10	**43**
Innovation	20	22	7	10	**59**
Total	**140**	**159**	**39**	**72**	**410**

Note: A darker shade of green color represents a higher frequency of co-occurrence. Likewise, a lighter shade of green represents a lower frequency of co-occurrence.

Regarding sustainability technologies, emission control is crucial to any sustainability strategy. However, its co-occurrence with digitization trends is lower than in other domains, especially computer-aided design. Nonetheless, sustainability technologies have a relatively balanced co-occurrence with all the digital trends presented, suggesting a multidimensional interaction and complementarity between digitization and sustainable solutions in the linear project domain.

As a result of the trend analysis, the classification of work fields relating to digitalization and sustainability is obtained:

- Design: Architectural design, Design, Structural design;
- Project management: Asset management, Cost analysis, Decision making, Facilities management, Information management, Project management, Public administration, and Road administration;
- Urban planning: Cities, Infrastructure planning, Regional planning, Road planning, Smart city, Smart infrastructures, Transportation Planning, Urban area, Urban growth, Urban planning, Urban renewal, and Urbanization;
- Infrastructure projects: Bridge engineering, Building construction, Buildings, Civil infrastructures, Linear infrastructure, Public infrastructures, Railroad transportation, Railroad tunnels, Railway construction, Road construction, Transport systems, Transportation, Tunnel engineering, Underground construction;
- Materials: Aggregates, Asphalt pavements, Building materials, Supply chains;
- Operation: Health monitoring, High-speed train, Inspection, Maintenance, Monitoring, Pavement maintenance, Public transport, Rapid transit, Street traffic control, Structural health monitoring, Traffic congestion, Traffic control, Vehicles;
- Construction and control: Budget control, Construction equipment, Accident prevention and risk analysis, Accident prevention, Disaster prevention, Risk assessment, and Road safety.

5. Conclusions

This study was oriented toward analyzing trends in the digitalization and sustainability of linear projects based on a bibliometric analysis of 419 scientific articles. From the results obtained, three main contributions stand out. First, the performance of the analysis has made it possible to discern various trends in the field. Notably, there is a steady increase in scientific production in the study area, reflecting a growing concern on the part of the research community to integrate digitalization and sustainability into

linear projects. Developed countries with significant infrastructure advances, such as China, Japan, the United Kingdom, the United States, and Australia, stand out as leading in scientific production in this area, creating a robust collaboration network and setting trends on the viability of incorporating sustainability principles in linear projects, using digital technologies. While in Latin America, there is still no significant contribution of research in the study area, also responding to the low indices of infrastructure development in countries in this region. In addition, three journals stand out in the publication of papers related to this field: Sustainability, Bautechnik, and Automation in Construction.

Secondly, through the analysis of scientific mapping, life cycle analysis management, digitalization of linear infrastructure, sustainable development, road construction, and road administration are recognized as the most relevant trends in digitalization and sustainability in linear projects. This co-word analysis shows the multidimensional perspective of research trends. Also, it marks the importance of interplay between clusters to drive towards holistic, efficient, and eco-conscious approaches to shape the future of linear infrastructure development, which must satisfy society's changing needs in terms of increased population climate conditions, among others.

Thirdly, various technological and methodological approaches are detected in the clusters oriented towards evaluating and integrating digital models assessing linear projects' sustainability throughout their life cycle stages. Digitalization makes it possible to simulate several scenarios to promote energy efficiency, emissions control, and environmental impact minimization, among others, thus reinforcing the inherent sustainability of these projects. A marked trend is towards integrating BIM with life cycle analysis techniques. BIM emerges as a pivotal catalyst, acting as a driving force for digitalization and offering a structured approach to sustainability integration.

The Smart City approach complements the confluence of digital models and sustainable practices. Through this lens, incorporating voluminous data sets from networked sensors facilitates management, ensuring the planning and construction of linear projects respond optimally to functional requirements and promote low environmental impact solutions.

Finally, this study shows a clear trend towards computer-aided design technologies, and its co-relation with sustainable development and life-cycle analysis suggests a strong link between technologies such as BIM, GIS, and computer vision to study their impact on crucial topics such as climate change and circular economy throughout the whole life cycle of projects. On the contrary, technologies such as Big Data, Artificial Intelligence, and Robotics have a weaker link with sustainability trends in general, with low and recent emergent publications according to the trend analysis, and have no strong relationships in the study of sustainable development clusters where technologies such as big data, IoT, computer vision and simulation have a link with the "sustainable development" concept. Still, no mention to artificial intelligence, machine learning, deep learning, automation, or robotics is found, suggesting a gap in this area of knowledge in linear projects.

6. Limitations and Future Research

The limitations of this study are (1) the non-use of search engines other than Scopus; (2) the exclusion of documents that were not found in the "article" and "review" types of document; (3) the study's sample selection was limited to Engineering, Computer Science, Energy, Environmental Science, and others; (4) the Bibliometrix library in R and VOS viewer are utilized instead of interviews, surveys, social network analysis, or content analysis; (5) the time between conducting the research, publishing it, and citing may cause variations in the trends identified in this study; (6) the increasing specialization and fragmentation of knowledge disciplines were excluded to facilitate identification of broader trends.

Future work could focus on (1) analyzing identified trends as solutions for practical and social problems; (2) extending analysis with qualitative studies, including interviews with prominent researchers, focus groups, and detailed content analysis of articles; and (3) identifying gaps between clusters and developing possible lines of research. Since there is a recent trend to integrate digitalization as a possible enabler for sustainable development,

we propose the following specific research developments as well, considering the current limitations of this study: (1) the internal relationships between each group in the thematic map results (niche, emerging or declining, motor and basic themes) to further understand digitalization and sustainability integration in each thematic group, (2) practical implementations of artificial intelligence and robotics technologies to enable sustainable development in linear projects, (3) comparisons between linear projects and buildings to understand better the research gaps in linear projects digitalization and sustainability integration.

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