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# Trends in interoperability in building information modeling (BIM) research: A scientometric analysis of authors and articles

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**Abstract**

Stakeholders with various backgrounds from different industries join together to realize a construction project that is unique in nature and is developed by an ad-hoc community. This type of formation shapes a dynamic and cooperative organization. Building information modeling (BIM) technology can be a valuable asset for sustainable, energy-efficient, safe and cost-effective building production. However, the content and context of the construction projects increase the size and complexity of data to be communicated, which in turn results in data loss throughout the demanding and costly project life cycle. Interoperability is the key to handle the data loss problem. The main aim of this research is to picture the status and trend in "interoperability" in BIM research with adopting bibliometric search and scientometric analysis for a broader understanding. Data were collected through an intensive investigation of interoperability in BIM research and selected through using Boolean Syntax, operators, and further limitations. 477 articles from the Scopus database were utilized for scientometric analysis and mapping. The research gaps were diagnosed. The potential future research needs and trends of interoperability in BIM research were proposed. Further, the classification of articles in the research field was suggested as "collaboration and sustainability-based", "BIM adoption", "BIM implementation at process-level", "BIM implementation in-country and at industry-level", and " BIM integration". The research results are expected to contribute to academicians, professionals and industry stakeholders for understanding the gaps and trends in interoperability in BIM research.

**Keywords**
Article analysis, Author analysis, Building Information Modeling, Interoperability, Scientometric analysis and mapping.

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## 1. Introduction

Most of the construction professionals in the construction industry prefer to use Building Information Modeling (BIM) to minimize data loss and ensure integrated high-performance construction project life cycle (Azhar et al., 2012, Onyenobi and Arayici, 2010). BIM is an information platform that is a single fully integrated database that can be created and used seamlessly and sequentially by the design team, construction team, and operators throughout the project lifecycle (Yalcinkaya and Singh, 2019b; Azhar et al., 2012; Shadram et al., 2016; Oh et al., 2015). BIM has the critical model information that plays role in increasing productivity and continuity, decreasing environmental damage, reducing waste of time and cost, adding value to the industry, provide the functional performance of occupants (Zhang et al., 2017; Ma et al., 2018; Heigermoser et al., 2019; Jin et al., 2019; Ugliotti et al., 2016). The best way of communication over data is the integration and interoperability. Architecture, engineering, construction, operation and facility management (AECO/FM) industry needs solutions for the interoperability problem, which is an obstacle for BIM implementation in turn for time and cost-effective construction projects. Interoperability is the way of using different systems to communicate with a basic communication protocol (Yalcinkaya and Singh, 2019a; Pauwels et al., 2011; Venugopal et al., 2012; Chen, et al., 2008). Therefore, protocols and standards have become important to prevent data loss during information sharing, use, and reuse, and for better coordination, and communication. There are international standards, file extensions and spreadsheet formats that are important tools to support BIM for increasing data integration, communication between stakeholders and data hierarchy in BIM research. However, problems in interoperability still exist which negatively effects BIM implementation, BIM adoption, and BIM-related industry concepts (Pauwels et al., 2011; Venugopal et al., 2012). Author and article based scientometric analysis and mapping of "interoperability" in BIM research were realized in this paper to enlighten the impact of authors and articles in the research field. The following parts of the paper express the related research in the field, the gaps, and trends in the research area and conclude with suggestions for future studies.

## 2. Research background

BIM, as a process of managing building information in an interoperable format, has been studied by researchers recently. BIM is used as a platform for integrated building information that can be utilized throughout the project lifecycle. The data loss throughout the project lifecycle is the main problem in technologically collaborative working environments. Interoperability is the key aspect of solving data loss problems for fully integrated systems. Interoperability is a prerequisite for an integrated system that improves the efficiency and effectiveness of project processes. Interoperability allows diverse software and hardware systems to work together in an integrated manner, which in turn enables integrated project delivery. A robust BIM adoption and implementation can be possible via solving interoperability problems.

### 2.1. BIM

For many years, architects and engineers that are interested in the construction industry tried to find new methods and ways to build better structures. With the rapid advancement of computing and information technologies in the past two decades, various systems and new technologies have been developed and deployed. The common meaning of BIM knowns as "a digital representation of physical and functional characteristics of a facility and a shared data from the beginning of the project" (Isikdag and Underwood, 2010; Yalcinkaya, 2016; Cavalliere et al., 2018). Because of the complexity of the BIM as an integrated data platform, systems integration, which depends on interoperability, becomes an important prerequisite to achieve efficient and effective adoption and implementation of BIM (Jiang et al., 2016; Vanlande et al., 2008; Pauwels et al., 2011).

## 2.2. Data exchange and interoperability

Construction project lifecycle consists of initiation, planning, construction, monitoring and controlling, closure, facilities management, and demolition processes throughout which multidisciplinary collaborative work occurs (Gu and London, 2010; Shen et al., 2010; Kent and Becerik-Gerber, 2010). The widespread responsibility area throughout the project life cycle triggers the requisition of interoperable applications for immediate adaptation to BIM adoption. The project team uses various tools to handle with above-mentioned processes. There is plenty of software to handle all the aspects of the project throughout the lifecycle. There is not any unique software that can manage the information of all professions. Interoperability is the seamless data exchange at the software level among diverse applications, each of which may have its own internal data structure (Grilo and Jardim-Goncalves, 2010). However, interoperability is not only the exchange of data but also the exchange of meaning. Interoperability is achieved by mapping parts of each participating application's internal data structure to a universal model and vice versa." (Tommasi et al., 2016; Grilo and Jardim-Goncalves, 2010). Standardization of data for transformation from the internal data structure to an adaptable universal data structure can be achieved through interoperability studies.

Data exchange is vitally needed along with the interoperability of data among cooperative units of projects. Therefore, interoperability via exchange formats is the key concept to determine the data exchange capability of different programs (Eastman et al., 2010; Venugopal et al, 2012). The transformed data consists beyond graphical data such as; geometrical features, energy-related, structural, quantity, material, cost, temporal, and so on. The quality of models increases with fully equipped object-oriented parametric data which leads the collaborative successful processes. For this reason, researchers work on interoperability issues to improve BIM implementations (Irizarry et al., 2013; Redmond et al., 2012; Shadram et al., 2016). BuildingSMART proposed a data standard called industry foundation classes (IFCs) to address the interoperability and data exchange issue for architecture, engineering, and construction professionals. Starting from 1997, IFC Schema is published and IFC4 is the latest issue as of today. Some of the commercial software systems for construction projects adopted an IFC data format for interoperability. However, there are still data errors and data loss (Jeong et al. 2009). In order to establish a collaborative working platform through BIM implementation, interoperability among data files of various disciplines has to be realized for robust data exchange.

- *IFC (Industry Foundation Class):* IFC format is used for information exchange (Redmond et al., 2012; Eastman et al., 2010; Pauwels et al, 2011; Venugopal et al., 2012). The data that it contains forms an object-oriented data model. The model has the system for representing the geometrical attributes and quantities of the objects. The objects like walls, columns, beams, slabs, doors, etc. are represented with their respective costs, schedule, technical information, etc. The latest version of the IFC standard is IFC 4 and approved as ISO 16739 standard. MVD (Model View Definition) defines the specification that is related to the data model. MVD classifies and describes the needed particular information for a specific use. The requested data for a specific validation model must be well defined in a contract.
- *IFD (International Framework for Dictionaries or Data Dictionaries):* While IFC is used to describe elements and processes, IFD, as a data dictionary, forms common understanding by defining the elements and their parameters. IFD is a feasible method, which allows generating product and processes equipped with specific data on IFC-BIM linked to existing knowledge systems for facility management. Moreover, data on the IFC-BIM has translation capability via IFD (Lin et al., 2016).

- *IDM (Information Delivery Manual):* IDM, as the standard of capturing the processes and information throughout the building lifecycle, ensures the quality of communication amongst project stakeholders through increasing the awareness and knowledge of participants with sharing data (Eastman et al., 2010; Arayici et al., 2018)
- *MVD (Model View Definition) / Cobie:* During the project lifecycle, data, content or IFC files' exchange methodology is specified by the model view definition (MVD), which is a standard that supports overall IFC schema (Lee et al., 2016a; Venugopal et al., 2015). National Institute of Building Sciences and building SMART have been working parallel with FM data exchange technologies. National Institute of Building Sciences approved Construction Operations Building Information Exchange (COBie) is an international standard for data exchange, which can be used for Facilities Management (FM). The data can be changed by using it not to lose any information from IFC during the operation (Yalcinkaya and Singh., 2015). COBie standard as part of its NBIMS-US (National Building Information Model) standard. The product of the joint effort of both institutions is Version 3 of the COBie standard. COBie, with the name "Basic IFC Handover View", is an official buildingSMART IFC MVD. BS 1192-4:2014 collaborative production of information Part4: Fulfilling employer's information exchange requirements using COBie – Code of practice is a British standard specifically dedicated to COBie. MVD is a diagram defining the method and content of information exchange for a specific use or workflow. MVD documentation leads the easy, fast, and consistent repeated data exchange among a variety of projects or software (Lee et al., 2016b; Venugopal et al., 2012). The object, relationship, representation, attribute, and concept need of receiving stakeholder is identified and the data to be exchanged is narrowed with an MVD. Since MVD are data-centric, the extent of and content of the model view is determined by the receiving stakeholder's information needs and by the workflow.
- *bSDD (Library respective building SMART Data Dictionary):* The building SMART Data Dictionary (bSDD) is a shared library serving for the AECO/FM industry, which consists of objects and attributes to build a common understanding among stakeholders through providing meaning. bSDD utilizes ISO 12006-3 ontology. The library shares data for construction project stakeholders (architects, engineers, owners, consultants, operators, manufacturers, suppliers, etc.) and is open access and international platform for sharing object and attribute data regardless of language. It is useful for fast, reduced cost, and high-quality data exchange for modeling. bSDD, as a semantic mapping tool, separates the words in any language and connects similar tools based on their meaning by identifying the concepts that the word represents in the construction industry. Common technical language library provides a platform, which may improve collaboration, coordination, cooperation, and communication through a robust knowledge share in the construction industry. bSDD not only translates the meaning but also rearranges the classification systems by mapping. An automatically generated ID number called GUID (the Global Unique Identifier) is needed in bSDD as a unique and language-dependent serial number. GUID number is assigned to each term and definition in bSDD.
- *Plug-in:* Even different BIM software belong to the same modeling category, they individually have own principles. Data exchange can also be achieved via plug-ins, by which the communication among programs is realized. Therefore, programs release new versions with associated plugins for export and import functions. the data exchange may be one-directional or bi-directional (Ugliotto et al., 2016; Gokce et al., 2007).

The time and content of the data to be shared are defined by IFC format, described by IFD format, and permitted by IDM format. The aforementioned standards identify the content of various interoperability levels. Understanding where to apply the format in the interoperability environment is possible with identifying data exchange format and the relationships.

## 3. Methodology

In this research, an intensive investigation of the literature is realized to acquire data for the scientometric analysis and mapping of the published works regarding interoperability in BIM to obtain an objective view of the current and future tendency of the research field. Researchers suggest three steps to apply for a powerful investigation of the literature (Booth et al., 2012; Petticrew and Roberts, 2005; Denyer and Tranfield, 2009). Conducted steps in this research are namely; planning the investigation, conducting the investigation, and documenting the investigation. The literature investigation approach used in this research has three-steps presented in Figure 1.

### 3.1. Planning scope of search

BIM search has a wide range of research branch diffused to each other for collaborative building delivery. The research fields consist of but not limited to project management, construction engineering and management, construction automation, structural analysis, performance analysis, facility management, integration of new technologies, and so on (Cao et al., 2018; Mangal and Cheng, 2018; Pinheiro et al., 2018; Ramaji and Memari, 2018; Rodrigues et al., 2018; Santos et al., 2017). This research focuses on interoperability in BIM research. The scope of the research covers the fields of AECO/FM research topics related to the whole project life cycle consisting of pre-construction, construction, and post-construction phases.

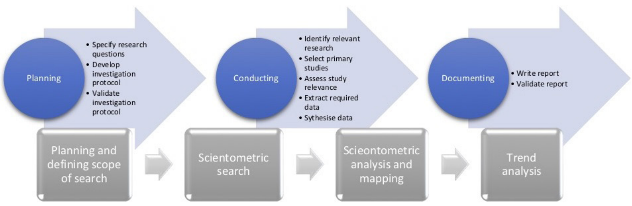


***Figure 1.*** *The three-step workflow of investigation of interoperability in BIM research.*

### 3.2. Conducting the research

The bibliometric search of articles of interoperability in BIM research was performed in one of the mainstream search engines for scientific researches that are called SCOPUS. Since Scopus coverage of sources is wider than any other database (Aghaei-Chadegani et al., 2013), this paper utilized the Scopus database for realizing its scope. Scopus's search API uses a system called Boolean Syntax for combining keywords with applying operators to consolidate search results for refined data at the end. The data from the Scopus database was used for scientometric analysis to apply science mapping over empirical data, which obtains a display of dynamic and structural aspects of the search area (Cobo et al., 2011). This method minimizes the tendency in prejudgment through intensive and extensive literature investigation of studies related to a particular subject and provides empirical evidence to provide a roadmap for future studies. The aim of using scientometric analysis and mapping in this research is to illustrate the relationship among the most impactful authors and articles in the domain in "interoperability" for BIM research. To realize this aim, VOSviewer software was used for visualizing networks using natural language processing (NLP) algorithms and text-mining. The imported data from the Scopus database about the authors and article was utilized to visualize, compute, and analyze in VOSviewer software. The covert analysis results visualized via mapping and clustering techniques.

### 3.3. Documenting search

In this research, a quantitative research technique was used to focus on understanding all aspects of interoperability in BIM research. The information gathered provides a deeper understanding of interoperability in the AECO/FM and was used to generate recommendations for the AECO/FM industry. Following the scientometric mapping, a scientometric analysis was realized in this study. The potential research direction in the field and possible emerging hot topics for future research were proposed for interoperability research for BIM.

## 4. Scientometric analysis results

The scientometric search was realized via using following terms and operators; TITLE_ABS_KEY: ({interoperability} AND {BIM} OR {Building Information Modelling} OR {Building Information Modeling}) (Figure 2). The search resulted in 2091 articles with predefined keywords in Scopus. Since English is identified as an academic language, the articles written in other languages were excluded (Butler and Visser, 2006). The language limitation decreased the results to 2052 articles. The other types of documents like conference proceedings were excluded from and only journal articles were included (Butler and Visser, 2006). The limitation narrowed the publication number to 886 articles. The search was refined by adding further limitations to consolidate articles related to interoperability in BIM research. The studies that include both interoperability and BIM at the same time were taken into consideration and the studies that include one of them but not both were excluded for a more focused search. Then the paper numbers were decreased to 518. The subject area of the articles was limited to the construction-related main subject areas. The Number of papers finally resulted in 477 articles to be used for the scientometric analysis.

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{interoperability} AND {BIM} OR {building information modeling} OR {building information modelling} AND ( LIMIT-
TO ( LANGUAGE , "English" ) ) AND ( EXCLUDE ( LANGUAGE , "Italian" ) OR EXCLUDE ( LANGUAGE , "French"
) OR EXCLUDE ( LANGUAGE , "German" ) OR EXCLUDE ( LANGUAGE , "Portuguese" ) OR EXCLUDE ( LANGU
AGE , "Spanish" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( SRCTYPE , "j" ) ) AND ( LIMIT-
TO ( EXACTKEYWORD , "Building Information Model - BIM" ) OR LIMIT-
TO ( EXACTKEYWORD , "Interoperability" ) OR LIMIT-TO ( EXACTKEYWORD , "Building Information
Modeling" ) OR LIMIT-TO ( EXACTKEYWORD , "Building Information Modelling" ) OR LIMIT-
TO ( EXACTKEYWORD , "Building Information Modeling (BIM)" ) OR LIMIT-TO ( EXACTKEYWORD , "Building
Information Modelling (BIM)" ) OR LIMIT-TO ( EXACTKEYWORD , "Data Interoperability" ) OR LIMIT-
TO ( EXACTKEYWORD , "Building Information Model" ) OR LIMIT-TO ( EXACTKEYWORD , "Building Information
Model (BIM)" ) ) AND ( LIMIT-TO ( SUBJAREA , "ENGI" ) OR LIMIT-TO ( SUBJAREA , "COMP" ) OR LIMIT-
TO ( SUBJAREA , "BUSI" ) OR LIMIT-TO ( SUBJAREA , "ENVI" ) OR LIMIT-
TO ( SUBJAREA , "SOCI" ) OR LIMIT-TO ( SUBJAREA , "ENER" ) OR LIMIT-
TO ( SUBJAREA , "DECI" ) OR LIMIT-TO ( SUBJAREA , "ARTS" ) OR LIMIT-
TO ( SUBJAREA , "ECON" ) OR LIMIT-
TO ( SUBJAREA , "MULT" ) ) AND ( EXCLUDE ( SUBJAREA , "MATH" ) OR EXCLUDE ( SUBJAREA , "EART" ) O
R EXCLUDE ( SUBJAREA , "MATE" ) OR EXCLUDE ( SUBJAREA , "CHEM" ) OR EXCLUDE ( SUBJAREA , "CEN
G" ) OR EXCLUDE ( SUBJAREA , "MEDI" ) OR EXCLUDE ( SUBJAREA , "PHYS" ) OR EXCLUDE ( SUBJAREA , "
BIOC" ) )
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***Figure 2.*** *Scientometric search input summary.*

### 4.1. The literature sample size

The first Scopus-indexed journal article mentioning "interoperability" in BIM for AECO/FM is in 2004. The literature from the first mention of 'interoperability' in BIM research from 2004 to date was reviewed. The number of papers was displayed yearly in Figure 3. There is considerable arise in article numbers to date. The interest in the research field critically accelerated in 2009 with a rate of approximately 385% increase. Especially in the last five years period (the article number of 2019 could not be completely monitored by the time the paper is prepared), the annual average article number increased around three times. The trend of interoperability in BIM research shows an incredibly high growth performance. The increasing interest in the research area evidences the major impact of it on the scientific platform. The graph visualizing the sharp growth line highlighted the possible improvement in the research field for the future.

The distribution of research outputs about "interoperability" in BIM shows that the researchers tend to publish about interoperability in Engineering (53.7%) and Computer Science (19%) research domains followed by Business and Management (14.1%). There are supportive contributions from other research domains such as; Environmental Science (3.3%), Social Sciences (3.1%), Decision Science (2.7%), Energy (2.5%), Arts and Humanities (1.1%), Economics (0.3%), and Multidisciplinary (0.3%). The technical structure of the research domain results in researchers' tendency on engineering and computer-based domains. Therefore, most of the interoperability studies place in Engineering and Computer Science research domains. In terms of research density, the technical

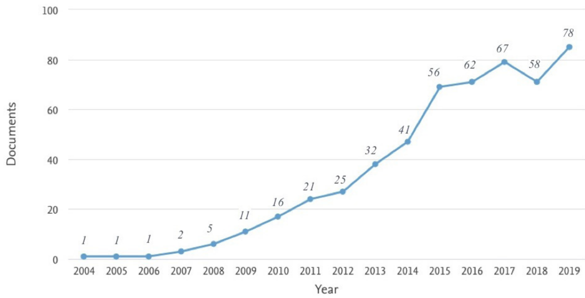



***Figure 3.*** *Yearly Number of papers from 2004 to 2019. (Note: The number of papers in 2019 is not complete as the articles selected in 2019 were up to the end of August 2019).*

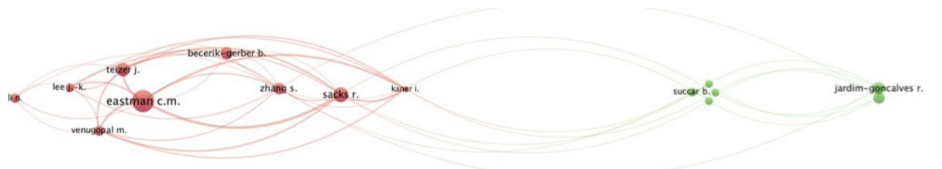
part of the research is followed by Business and Management, which includes a major implementation area such as facility management. However, the industry has yet to considerably utilize interoperability throughout AECO/FM activities.

### 4.2. Scientometric analysis and mapping of authors

Authors that studied about interoperability in BIM were mapped via VOSviewer software to understand their impact on the research field and relatedness among each other. Figure 4 shows the network visualization map of citation analysis of authors with a minimum number of 1 document and with a minimum number of 310 citations per document of an author. There were 15 authors, who met the threshold. Data related to authors were tabulated in Table 1. Figure 4 depicts a sharp distinction that represents the research tendency of authors. From afar perspective, research areas may be separated into two branches namely; *interoperability in BIM theory research* and *interoperability in BIM practice research. "Interoperability in BIM theory research"* cluster represents the studies including ontology, framework, standards, and technical integration kinds of BIM theory approaches. *"Interoperability in BIM practice research"* cluster represents the studies including BIM implementation approaches related to applications, adoption, implementation, and practical integration of all BIM framework, standards, codes and etc.

The citation analysis of authors result was presented with a network visualization diagram in Figure 4. The lines, colors, and distance between circles show the relatedness of author pairs by mutual citations. The color of the circle indicates in which cluster the author's scope falls within. The link lines between the authors displays inter-relations among authors. The distance between authors identifies the relatedness of the authors in terms of citation links. Figure 4 illustrates circles to represent authors. The size of circles and labels of the author is determined by the weight of the author. The higher contribution of the author to the research area, the larger is the size of the circle and the font. *R.L.R. Jardim-Goncalves, C.M. Eastman, R. Sacks, and A. Grillo* are among the most influential authors.

Seven major quantitative factors; Field-Weighted Citation Impact (FWCI), the article number of author related to interoperability in BIM research, the total article number of authors, the percentage of the related field article number of the author within all her/his article numbers, H-Index (Hirsch Index), link, total link strength (TLS), and average normalized citation data about the authors were tabulated in Table 1. FWCI metric is useful to benchmark regardless of differences in size, disciplinary profile, age and publication type composition, and provides a useful way to evaluate the prestige of a researcher's citation performance. FWCI considers the differences in research behavior across disciplines. FWCI is the ratio of the total citations received by the author's output, and the total citations that would be expected based on the average of the subject field. An FWCI of greater than 1.00 indicates that the publications have been cited more than would be expected based on the world average for similar publications. FWCI metric was used to benchmark and evaluate the prestige of a researcher's citation performance. The FWCI results depict that B. Becerik-Gerber is the highest-ranked author in the field of "Buildings | Construction Industry | Information Modeling" (the




Interoperability in BIM Practice research    Interoperability in BIM Theory research

***Figure 4.*** *Network map visualization of authors focused on interoperability in BIM research (between 2004-2019).*

Scopus defined field) in terms of citation performance compared to other researchers. Article numbers related to interoperability in BIM research show the authors' tendency in the research field. R.I.R. Jardim-Goncalves, C.M. Eastman, and R. Sacks have the highest number of articles related to interoperability in the BIM research field. The total number of articles indicates the contribution of the author in the whole literature. *R.I.R. Jardim-Goncalves, J. Teizer, and C.M. Eastman* have the highest total number of articles. H-index measures the impact of an author on the literature. The highest H-index belongs to *J. Teizer, R. Sacks, B. Becerik-Gerber, and C.M. Eastman*. The links attribute indicates the interrelatedness of the given author to other authors. The total link strength attribute indicates the strength of the relationship of an author with other authors. The highest scored link number belongs to *J. Zhang, R. Sacks, I. Kaner, C.M. Eastman, and J. Teizer.* However, TLS shows the most interrelated authors in terms of citations are J. Teizer, I. Kaner, and M. Venuggopal. The average normalized citation indicates the average normalized number of citations received by the documents published by an author. However, *C.M. Eastman, R. Sacks, and J. Teizer* score the highest three average normalized citation values between 2004 and 2019 among interoperability in BIM researchers.

The highest FWCI, H-index, links, total link strength, and average normalized citation scores belong to authors in the Interoperability in BIM Practice (Table 1). The results of the citation analysis of authors indicate that the major impact authors and articles of the interoperability in BIM research is within *"the Interoperability in BIM Practice"*. Authors studying the interoperability issues in BIM practice may get more citations, stronger links with other authors and may increase H-index and FWCI scores.

### 4.3. Scientometric analysis and mapping of articles

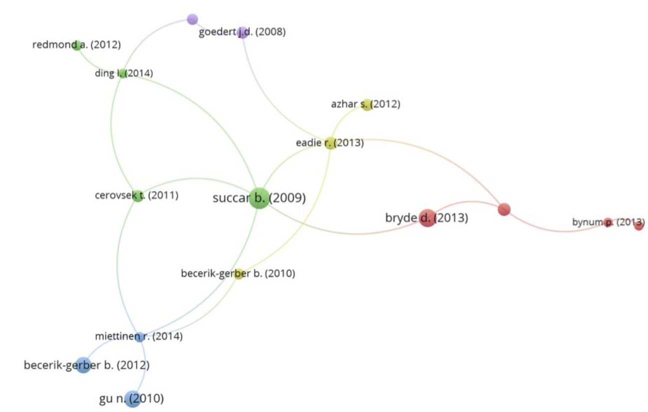
Articles about interoperability in BIM research were mapped via VOSviewer to understand their impact on literature. Figure 5 shows the network visualization map of citation analysis of articles based on bibliographic data with a minimum number of 100 citations per document of an author. There are 16 authors, who met the criteria were represented in Figure 5. The color of an article identifies the cluster that the article belongs to. The articles were grouped in five clusters (Figure 5). The name of the clusters was determined according to the field of study that the article belongs to (Table 2) *namely collaboration and sustainability (red-coded), BIM adoption (green-coded), BIM implementation at the process level (blue-coded), BIM implementation in-country and at industry-level (yellow-coded), and BIM integration (purple-coded).*

***Table 1.*** *The authors focused on the research of interoperability in BIM (between 2004-2019).*

| Cluster Name | Author | FWCI | Ar. Num. related to Subject | Total Num. of Art. | H-index | Link | TLS | Ave. Norm. Citation |
|---|---|---|---|---|---|---|---|---|
| *Interoperability in BIM Practice* (Red-coded) | Becerik-Gerber, B. | 1.64 | 3 | 124 | 30 | 5 | 5 | 10,33 |
| | Eastman, C.M. | 1.29 | 23 | 146 | 30 | 8 | 16 | 21,03 |
| | Kaner, I. | --- | 4 | 4 | 4 | 10 | 43 | 4,08 |
| | Lee, J.K. | 1.29 | 5 | 48 | 11 | 7 | 25 | 6,61 |
| | Li, N. | 1.29 | 1 | 58 | 14 | 5 | 6 | 7,49 |
| | Sacks, R. | 1.29 | 13 | 123 | 34 | 10 | 6 | 13,07 |
| | Teizer, J. | 1.29 | 5 | 152 | 36 | 8 | 49 | 11,75 |
| | Venuggopal, M. | 1.29 | 2 | 9 | 16 | 7 | 40 | 7,77 |
| | Zhang, S. | 1.29 | 2 | 17 | 11 | 11 | 27 | 9,40 |
| *Interoperability in BIM Theory (Green-coded)* | Broquetas, M. | --- | 1 | 1 | 1 | 5 | 5 | 5,97 |
| | Bryde, D. | 1.29 | 1 | 50 | 15 | 5 | 5 | 5,97 |
| | Grilo, A. | 0.93 | 2 | 90 | 14 | 5 | 11 | 9,78 |
| | Jardim-Gonçalves, R.L.R. | 0.93 | 44 | 248 | 20 | 5 | 11 | 10,45 |
| | Succar, B. | 1.29 | 3 | 6 | 6 | 4 | 4 | 6,92 |
| | Volm, J.M. | --- | 2 | 2 | 2 | 5 | 5 | 5,97 |

* Topic Field-Weighted Citation Impact: shows how well the documents in the topic are cited compared to similar documents. A value greater than 1.00 means the documents are more cited than expected.

* "---" Refers to the documents which were published earlier than 3 years. So that Topic FWCI cannot be calculated.




| Blue-coded (BIM Implementation at Process Level) | Green-coded (BIM Adoption) | Purple-coded (BIM Integration-based) | Yellow-coded (BIM Implementation at Country and Industry Level) | Red-Coded (Collaboration and Sustainability) |
|---|---|---|---|---|

***Figure 5.*** *Network map visualization of articles focused on interoperability in BIM research (between 2004-2019).*

***Table 2.*** *The articles focused on the research field of interoperability in BIM (between 2004-2019).*

| Cluster Name | Article | Title | FWCI | Link | Citation | Normalized Citation |
|---|---|---|---|---|---|---|
| Collaboration and Sustainability-based (Red-coded) | Bryde, et al. (2013) | The project benefits of building information modelling (BIM) | 18.56 | 2 | 347 | 6,11 |
| | Bynum et al. (2013) | Building information modeling in support of sustainable design and construction | 9.33 | 2 | 106 | 1,87 |
| | Grillo and Jardim-Goncalves (2010) | Value proposition on interoperability of BIM and collaborative working environment | 9.74 | 3 | 188 | 1,04 |
| | Taylor and Bernstein (2009) | Paradigm trajectories of building information modeling practice in project networks | 4.38 | 1 | 101 | 1,04 |
| BIM Adoption (Green-coded) | Cerovsek (2011) | A review and outlook for a "Building Information Model" (BIM): A multi-standpoint framework for technological development | 7.77 | 3 | 163 | 3,61 |
| | Ding et al. (2014) | Building Information modeling (BIM) application framework: The process of expanding from 3D to computable nD | 7.59 | 4 | 100 | 3,56 |
| | Redmont et al. (2012) | Exploring how information exchanges can be enhanced through Cloud BIM | 6.52 | 1 | 117 | 2,30 |
| | Succar (2009) | Building information modelling framework: A research and delivery foundation for industry stakeholders | 12.30 | 5 | 498 | 5,13 |
| BIM Implementation at Process Level (Blue-coded) | Becerik-Gerber et al. (2012) | Application areas and data requirements for BIM-enabled facilities management | 15.26 | 1 | 287 | 5,64 |
| | Gu and London (2010) | Understanding and facilitating BIM adoption in the AEC industry | 8.29 | 1 | 308 | 3,89 |
| | Miettinen and Paavola (2014) | Beyond the BIM utopia: Approaches to the development and implementation of building information modeling | 9.59 | 5 | 124 | 4,42 |
| BIM Implementation at Country and Industry Level (Yellow-coded) | Azhar et al. (2012) | Building information modeling (BIM): Now and beyond | 7.81 | 1 | 164 | 3,22 |
| | Becerik-Gerber and Rice (2010) | The perceived value of building information modeling in the U.S. building industry | 4.40 | 2 | 141 | 1,78 |
| | Eadie et al. (2013) | BIM implementing throughout the UK construction project lifecycle: An analysis | 6.08 | 5 | 188 | 3,31 |
| BIM Integration (Purple-coded) | Goedert and Meadati (2008) | Integrating construction process documentation into building information modeling | 5.98 | 2 | 162 | 2,11 |
| | Irizarry et al. (2013) | Integrating BIM and GIS to improve the visual monitoring of construction supply chain management | 10.08 | 2 | 147 | 2,59 |

The articles were displayed in circles and labels (Figure 5). The size of the circle of an article was determined by its weight. A larger size of the circle and label represents a higher weight for an article. The distance between two articles in the network visualization map shows the relatedness of the articles in terms of citation links. In general, close location of two articles in the network visualization map represents a stronger relatedness.

Data related to the citation analysis of articles about interoperability in BIM were tabulated in Table 2, including four major quantitative factors as FWCI, links, citation, and normalized citation values. FWCI metric indicates how the number of citations received by an author's article compares with the average number of citations received by all other analogous articles indexed in the Scopus database. An FWCI value greater than 1.00 indicates that the article is cited more than would be expected based on the average citation for similar articles. The FWCI of *Bryde et al.* (2013) was cited 1856% times more than expected with a score of 18.56 means that the output. Even the lowest FWCI value of 5,98 evidenced that the article was cited 598% times more than the expected citation numbers. The strong citation links between articles visualized by lines. Lines between articles display links. The average normalized citation factor indicates the average normalized number of citations received by the published article. Both of the FWCI and normalized citation results show that the articles with the highest impact in interoperability in BIM literature are *Bryde et al. (2013), Becerik-Gerber et al. (2012), and Succar (2009).* The link values differ from the FWCI and normalized citation values. The link values show that the article that has the most widespread impact is Succar's (2009) research with a 5 link to each article within every 5 clusters. Broad diffusion impact of this article is because of its generic content composed of industry stakeholders for framing BIM adoption.

## 5. Discussion of the results

Based on the scientometric analysis of bibliometric data about interoperability in BIM related topics, following future research trend directions were recommended. As stated in the science mapping of authors and articles evidenced that the research topics are generically grouped under *interoperability in BIM practice and interoperability in BIM theory* headings. According to citation analysis of articles interoperability in BIM research is mainly categorized into five groups such as;

a. Collaboration and Sustainability (red-coded in Figure 5)

b. BIM Adoption (green-coded in Figure 5)

c. BIM Implementation at Process-level (blue-coded in Figure 5)

d. BIM Implementation in-Country and at Industry-level (yellow-coded in Figure 5)

e. BIM Integration (purple-coded in Figure 5)

According to the results of science mapping of articles (Figure 5 and Table 2) *"BIM adoption"* studies interact with 4 clusters (*"BIM implementation in-country and at industry-level"* studies, *"BIM integration"* studies, *"BIM implementation at process-level", and "collaboration and sustainability-based"* studies). *"BIM implementation in-country and at industry-level"* studies also interact 4 clusters (*"BIM adoption" studies, "BIM integration"* studies, *"BIM implementation at process-level", and "collaboration and sustainability-based"* studies). Whereas, *"collaboration and sustainability-based"* studies, *"BIM implementation at process level"* and *"BIM integration"* studies each interact only 2 clusters. Less interacting clusters have research gaps in terms of integrating the other subjects' perspectives. Therefore, researchers should consider studying the combination of process-level BIM implementation, integration, collaboration, and sustainability issues in their future researches to have a high impact within interoperability in BIM research.

**5.1. Leading researchers of interoperability in BIM research**

According to the author analysis, the interoperability research by authors mainly accumulated under *"BIM theory"* and *"BIM practice"* categories. As seen in Figure 4, the interoperability in *"BIM theory"* researches (green coded authors in Figure 4) are clearly separated into two groups namely, *"BIM framework"* (Succar, B.; Broquetas, M.; Bryde, D.; Volm, J.M.) and *"BIM advantages and research areas"* (Jardim-Goncalves, R.L.R.; Grilo, A.) sub-categories. However, there is not any clear distinction between interoperability in *"BIM practice"* researches. When one focuses on Figure 4 and Table 1 and on the authors' published documents, one can understand that the interoperability in BIM practice research (red coded authors in Figure 4) categories can be interpreted in four sub-categories namely *industry-based approaches* (Becerik-Gerber, B.), *process-based approaches* (Li, N.; Becerik-Gerber, B.), *BIM data exchange* (Eastman, C.M.; Sacks, R.; Kaner, I.; Zhang, S.), and *BIM information exchange* (Eastman, C.M.; Teizer, J.; Venuggopal, M.; Lee, J.K.).

The most influential authors in the field are *Teizer, S.; Sacks, R.; Eastman, C.M. and Becerik-Gerber, B.* Apart from this, since interoperability subject places in the technical part of BIM research, *"BIM practice"* studies are more in need of the solution of interoperability related problems than *"BIM theory"* researches. Figure 4 indicates that the researches about interoperability in *"BIM practice"* attract more audiences than *"BIM theory"* research. Furthermore, with a chronological point of view, from the emergence of BIM technology as an information platform to the current time of practical application of BIM, the research focus skewed to more practical problems like interoperability. Therefore, the research trend of interoperability in BIM seems to examine the practical implications and implementation opportunities for BIM technology.

**5.2. Leading studies of interoperability in BIM research**

Article Analysis results suggest that the studies are mainly clustered into five categories. Article analysis obtained more detailed cluster results rather than author analysis. As seen in the Figure 5 interoperability in BIM research was divided into five main clusters called; *"collaboration and sustainability-based"* (red-coded articles), *"BIM adoption"* (green-coded), *"BIM implementation at process-level"* (blue-coded), *"BIM implementation in-country and at industry-level"* (yellow-coded), *"BIM integration"* (purple-coded). In accordance with the results, since the subject relies on the technical side of the BIM research area, the acceleration in the number of new studies is rapid. Therefore, FWCI scores indicate an extraordinarily and unexpectedly very high based on the similar articles' citation data. The article analysis results indicate that *"collaboration and sustainability-based"* studies are the most influential researches in the field. The impact of the articles related to collaboration and sustainability increases in time. The reason for this is collaboration via BIM platform can be achieved successfully with improvements in the BIM adoption, so that the building information is available to use in sustainability and in other design, construction, operation, and facility management studies. The next highest impact articles fall within the

*"BIM implementation at process level"* category. Chronologically, the studies focused on model development, model interaction, model integration, implementation of model information and so on in the first phase of the BIM research. However, a process-based point of view in BIM implementation researches is relatively new and needs to be further analyzed. The third highest impact research category is the *"BIM adaption",* in which model-based technological issues are addressed. Model development, improvement, and integration-related researches fall within this category, which has attracted many researchers since the emergence of BIM and will always be in the focus for further developments in the model. However, there are still gaps in *"BIM implementation in-country and industry-level"* and "BIM integration' related studies in the interoperability field. The BIM adaptation occurs in the model, modeling, and process level, therefore country-based approaches and BIM integration with new technologies are still could not reach the expected maturity.

The interoperability may be a barrier for the Level 2 and Level 3 BIM implementation, in which information sharing and exchange of information across different stages of a construction project should be smooth. BIM adoption and BIM integration studies should extend to all stages of the project rather than only in the design stage. Integrated project processes require improvements in the systems integration of BIM models. Integrated project delivery, operations, and facility management may assure sustainable and intelligent buildings. This paper suggests spreading the research tendency to all processes allowing integration for collaborative and sustainable approaches throughout the project lifecycle with in-country and industry-level implementation approaches.

### 5.3. Research limitations

The paper covers the author and article analysis in interoperability in BIM research. However, future studies in interoperability in BIM research may analyze bibliographic coupling of organizations and countries or apply co-citation and co-authorship analysis for further detailed findings. The language limitation may not be applied in the bibliometric search so that the insight of studies encompasses a global perspective. Books, reviews, conference proceedings or other sources can also be included in the journal articles to capture all points of view from completed and on-going projects. The data for this research was acquired from the Scopus database. However, future studies may merge data from all databases for more robust findings. The stability of data is an important limitation for this type of researches. Therefore, a dynamic data import and dynamic data visualization can be a solution for up-to-date scientometric analysis. Furthermore, the 2D dimensional visualization of data is a barrier in rapidly understanding the gaps and trends. 3D computation of bibliometric data with knowledge graph representation may improve the mapping technique.

## 6. Conclusion

Interoperability in BIM research has gained significant growth in literature. However, there are still BIM implementation and adoption problems related to data exchange inefficiencies causing limitations in integration, collaboration, and communication in AECO/FM activities throughout the project lifecycle. This paper realized a scientometric analysis and mapping of authors and articles to address the research gaps and tendencies in the field and proposed future trend opportunities for the research field of interoperability in BIM. BIM adoption and BIM implementation in-country and at the industry-level studies interact with all other research subjects. Therefore, the emphasis should be on collaboration and sustainability-based, BIM implementation at the process, and BIM integration-based studies. The scientometric analysis results reveal that articles those have generic context such as; BIM framework, BIM implementation advantages, industry level BIM adoption have high impact in the research field. The next trending articles are related to integrated BIM models for better BIM implementation in project management issues, a collaborative platform, approaches for better BIM implementation, respectively. However, more incorporated research approaches in articles are needed in future studies to have a holistic point of view and integrated implementations in the field. Country-based researches and BIM integration-related studies have the potential to pull more attention in the near future. The results of this research serve all AECO/FM industry stakeholders and academics from the field for a broad understanding of current research gaps and trends in interoperability in BIM research. The data sample adopted in this study was from journal articles focusing on academic research, the articles, and the authors, and excludes AECO/FM industry practices and improvements. Future research may be more inclusive of industry practitioners' data to further enrich findings.

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