

## Article

# BIM and Mechanical Engineering—A Cross-Disciplinary Analysis

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**Abstract:** Mechanical Engineering (ME) includes the design, manufacturing, assembly, and maintenance of mechanical subsystems for Architecture, Engineering, Construction, and Owner-Operator (AECO) projects. The intense adoption of information and communication technology in the AECO started with building product modelling, which was originally pioneered in the ME domain (i.e., automotive industry). The complexity and limited openness of product models paved the way for Building Information Modelling (BIM). Today, BIM workflows require an exchange of interoperable architecture, structure, and MEP/HVAC models and their seamless integration into a shared BIM model. Many specialized ME systems exist (i.e., medical gases and vacuum) for which BIM is not mature enough and where the role of BIM has not yet been studied. Therefore, a comprehensive cross-disciplinary analysis on the mutual influence of the BIM and the ME domain is needed for researchers and professionals. It identifies research fields and trends at the intersection of BIM and ME and analyzes their scope, limitations, and requirements for future extensions of BIM for better integration with ME. The analysis is based on an extensive literature search considering the interdisciplinary nature of ME. The initial collection of papers has undergone a rigorous bibliometric analysis that used a text mining approach for validation. Results show the field “Industry 4.0” as the most prosperous BIM influencing research field, followed by “Energy optimisation” and “Environmental Product Declaration”, while identifying “Geometric optimisation” and “Reinforced material” as the trendiest. Finally, conclusions on the impact of BIM on ME were drawn and 11 research opportunities were identified. This paper provides directions for studies where research is focused on the integration of ME systems in BIM workflows and on the extension of BIM capability to model future ME systems.



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**Keywords:** BIM; mechanical engineering; cross-disciplinary analysis; AECO

## 1. Introduction

Spanning from the production of a blank sheet of paper, to the construction process of the Burj Khalifa or the latest aircraft: Mechanical Engineering (ME) has an impact on every man-made engineering achievement. There are products where ME is indispensable throughout the majority of its lifecycle activities—such as design, manufacturing and product maintenance (e.g., car industry, tool manufacturing)—while with other products ME is involved only partially in a specific engineering process (e.g., built environment industry). Built environment (BE), represented by the joint domains of Architecture, Engineering, Construction and Owner-Operator (AECO), is a domain where ME provides an utterly important consultancy responsible for the design and installation of typical mechanical subsystems like heating, ventilation, air conditioning, and plumbing. The mechanical subsystems planned for BE projects can be designed using Building Information Modelling (BIM) [1].

For the BE, BIM can be viewed as a model-centric, collaboration-rewarding, and product lifecycle-oriented methodology that is more holistic than the other existing computer-aided methods used by the AECO, namely:

- Drafting-centric or CAD-centric (e.g., CAD drawings),



- Product-centric (e.g., LCCA—LifeCycle Cost Analysis),
- Model-centric (e.g., product modelling using STEP—Standard for the Exchange of Product model data), or
- Process-centric (e.g., project scheduling, workflow management using BPMN—Business Process Modelling Notation).

BIM is a methodology that transitions BE to the digital era [2] and, therefore, the industry is catching up on the automotive, petrochemical, shipbuilding, and aerospace industries. The maturity of the BIM implementation can be described through the Levels of Maturity (Level 0—paper-based drawings employing CAD and low coordination, Level 1—partial 3D modelling with proprietary formats exchange, Level 2—federated BIM with a higher level of coordination using Common Data Environment, and Level 3—fully integrated and interoperable cloud-based BIM) which distinguishes the degrees of coordination and collaboration between the stakeholders, use of exchange formats, and depth of the exchanged information [3].

The industries, mostly ME dominated fields, have built on the product models [4] utilized with Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM) [5]. Despite the advanced use of product models, attention is mostly paid to the single field models used to automate the generation and coordination of 2D documentation and less to the lifecycle product data management. The approach is mainly proprietary and is different from the BE domain where BIM enables open standardized and interoperable solutions throughout the building lifecycle with global influence [6]. BIM also encourages discussions beyond the technical systems, such as socio-technical systems [7]. It can be concluded that there are differences in the notion of digitalization between the BE and ME: the ME is still deeply rooted in CAD 2D/3D approaches, while the BE domain is already moving from the CAD-based to the open BIM-standardized digitalization. Pioneering steps towards BIM in ME include early observations that BIM is making design and construction easier by creating ways to design, lay out, and allow for multidiscipline coordination in 3D [8]; automating the extraction of information from textual descriptions and schematic diagrams in construction documents for HVAC systems [9]; providing favorable analysis of practicing BIM in the mechanical industry sector [10], and automating the reconstruction of mechanical systems in BIM from legacy 2D drawings [11]. Recent research has led to the formulation of the IDM (Integrated Delivery Manual) standard from the perspective of the actual designs that are integrating process maps covering architecture, structure, plumbing, ME, and electrical engineering, and are thus showing how to realize BIM-based collaborative work [12]. Therefore, mechanical engineers working in the BE domain are switching from CAD models to the more open and information model-centric BIM models where exchange formats are often connected to the Industry Foundation Classes (IFC) standardized data model, developed by BuildingSMART. IFC can define, for example, the components of buildings, manufactured products, mechanical and electrical systems and logically codify identities, semantics, attributes, objects, relationships, concepts, and processes. IFC files are neutral, open, and standardized: created to promote full interoperability within BIM [13]. This will influence the ME itself, which is likely to shift from an isolated workflow to a more open and lifecycle-based modelling workflow.

### 1.1. Mechanical Subsystems in AECO Projects

There are fields that require active collaboration between ME and the AECO, such as energy efficiency [14], HVAC [15], design coordination [16], cost estimation [17], mechanical equipment [18], structural simulation with a finite element model [19], the design of residential containers, etc. For example: to ensure the structural integrity of a residential container, the mechanical design considers the steel profiles and sheets as well as the methods of joining (screwing and welding). Complementary to this, the AECO takes over with the architectural design—the arrangement of containers and the interior design of the furniture.



It can be assumed that BIM might create benefits for other subfields of ME. To prove that, research was carried out to identify all fields in the intersection between ME and BIM. The research also explores future research directions for the specialization of a BIM approach inside ME.

To get acquainted with different approaches to literature analysis we carried out an initial reading of publications from the field of systematic literature research [20–23] which served us as a base for the development of a research methodology.

### 1.2. Research Contributions

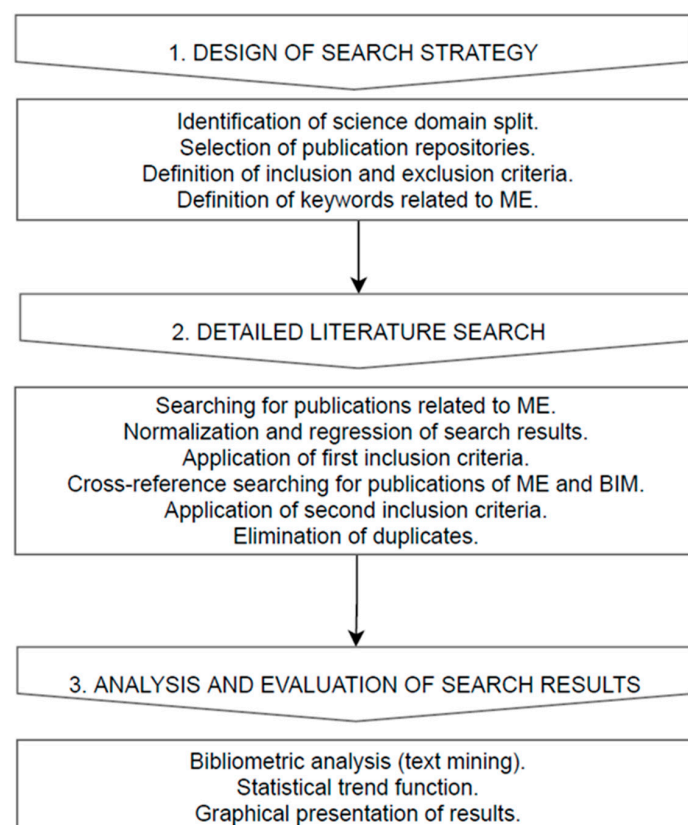
The two scientific fields, ME and AECO, are individually thoroughly researched. In our research, however, we focused on the intersection between the ME fields and BIM as a subfield of the AECO.

Therefore, the paper aims to comprehensively analyze literature published after the emergence of BIM to find potential research and applications of BIM within ME subfields. The methodology implements a search strategy, a rigorous bibliometric analysis, a text mining approach, and a detailed assessment of the narrowed set of selected papers. With this in mind, the following research questions were defined:

1. What research fields exist at the intersection of BIM and ME?
2. What are the trends in the research fields from the intersection of BIM and ME?
3. What are the knowledge gaps and open research topics and what is the future research agenda for BIM in ME?

## 2. Methodology

To ensure a systematic, robust, and repeatable literature analysis process, the Kitchenham guidelines [24] were adopted. A methodology that involved a literature search, analysis, and evaluation of search results has been defined according to the guidelines, encompassing three steps (Figure 1).



**Figure 1.** Methodology for the literature search, analysis, and an evaluation of search results.



### 2.1. Step 1: Design of the Search Strategy

The design of the search strategy and the definition of inclusion and exclusion criteria for the first and the second research questions that were related to the research fields at the intersection of BIM and ME and the main trends, included the following steps:

- a. Identification of the science domain-split related to the AECO and ME science fields,
- b. Selection of repositories for publication retrieval,
- c. Definition of inclusion and exclusion criteria,
- d. Definition of specific keywords related to ME.

ME is a broad engineering field; therefore, in the first step, an initial search was performed within five science fields (Engineering, Computer Science, Energy, Environmental Science, and Material Science) which are significant for both ME and AECO. The initial set of keywords were selected from recent scientific literature related to the trends and applications of mechanical engineering [25], as indicated in Table 1.

**Table 1.** Science fields influencing Architecture, Engineering, Construction, and Owner-Operator (AECO) and Mechanical Engineering (ME) and the corresponding 52 specific keywords as defined in the first phase of the search strategy.

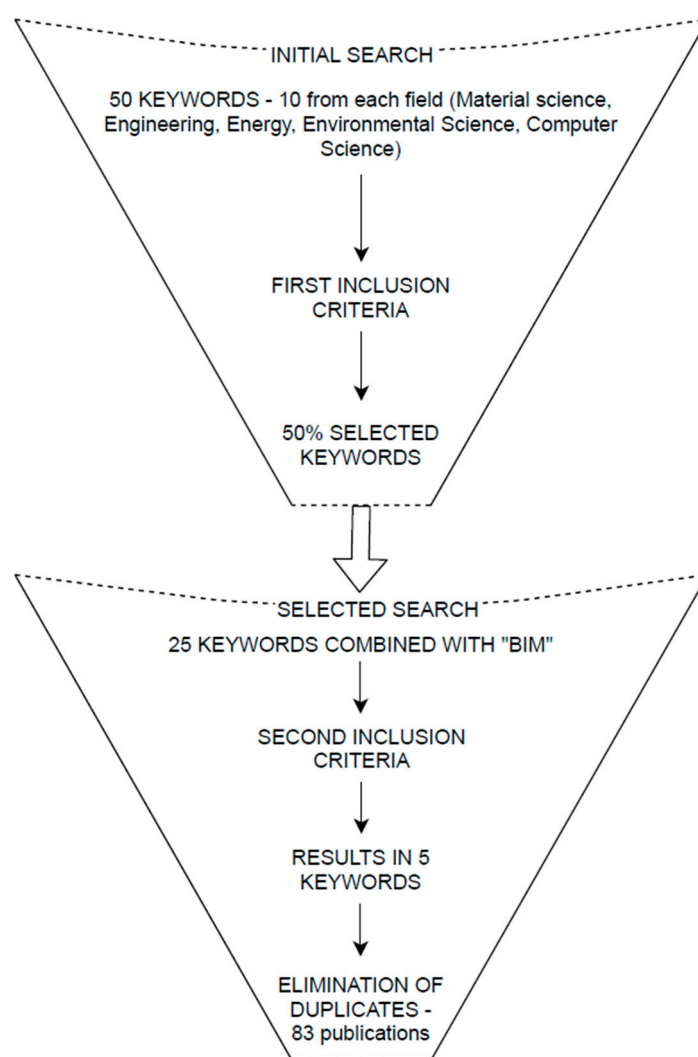
Science Field Related to ME and AECO	Specific Keywords (Subfields)
Material Science	Construction material; Material supply; Mechanical property; Reinforced material; Carbon steel; Composite; Fatigue load; Nanomaterial; Polymer; Microstructure.
Engineering	Mechanical Design; Process Automation; Industry 4.0; Sustainable Design; Product Modelling; Mechanical, Electrical and Plumbing; Manufacturing; Production; 3D printing; Robotics.
Energy	Thermodynamic; Energy system; Green energy; Energy efficiency; Heating, ventilating and air conditioning; Energy optimisation; Energy conservation; CO <sub>2</sub> emission; Heat transfer; Thermal energy.
Environmental Science	Environmental protection; Environmental impact; Greenhouse gas emissions; Climate change; Renewable resources; Air pollution; Water supply; Environmental Design; Lifecycle cost analysis; Environmental Product Declaration.
Computer Science	Computer aided engineering; Computer Aided Design; Computer integrated manufacturing; Computational fluid dynamics; Parametric modelling; Meta modelling; Geometric optimisation; Numerical optimisation; Model based technique; Finite element method.

### 2.2. Step 2: Detailed Literature Search

In the second step, a detailed literature search was performed (Figure 2). The step was subdivided into two phases. The first phase (a, b, c) involved a specific keyword search across the ME related fields. In the second phase (d, e, f), results from the first phase were combined with the keyword “BIM” for a new search:

- a. Search and retrieval of publications related to ME,
- b. Normalization and regression of search results,
- c. Application of first inclusion criteria,
- d. Cross-reference search for publications with keywords from ME and BIM,
- e. Application of second inclusion criteria,
- f. Elimination of duplicates.





**Figure 2.** Two phases of the literature search.

The literature search inclusion criteria were defined to reduce the result-set in the first phase. The first inclusion criteria were:

- The number of publications has positive trend over the years (regression curve of normalized results is ascending),
- The five steepest graphs from each field are selected for the next phase.

In the second phase, further inclusion criteria narrowed the set of keywords and publications into the most prosperous areas at the intersection of BIM and ME.

The second inclusion criteria applied were:

- The connected graph of normalized results is ascending,
- From the single field the most upward trend is selected and duplicated publications are removed if they exist.

The remaining publications were then used as the input corpus for text mining with term frequency analysis. The purpose of the analysis was to validate the appropriateness of the resulting set of publications. Results not satisfying all the inclusion criteria of a particular phase were excluded from further research.

In both searching phases, the Scopus search engine was used. Based on the European Classification of Research Activities (CERIF—CERCS) [26], it was found that ME does not have an explicitly named scientific field, but is included in other fields which are also related to AECO. The science fields included in the search (in the fields: Abstract, Title, and Keywords) were: Engineering, Computer Science, Energy, Environmental Science



and Material Science. The logical operator in the cases of combined multiple-searched keywords was always AND. The Publication Type field of the search was restricted to Journals and Books published in the time period of 2007–2020. The time period corresponds to the beginnings of BIM research. Additionally, other known academic databases—namely WoS, Google Scholar, ASCE Library, Wiley, and IEEE—were used.

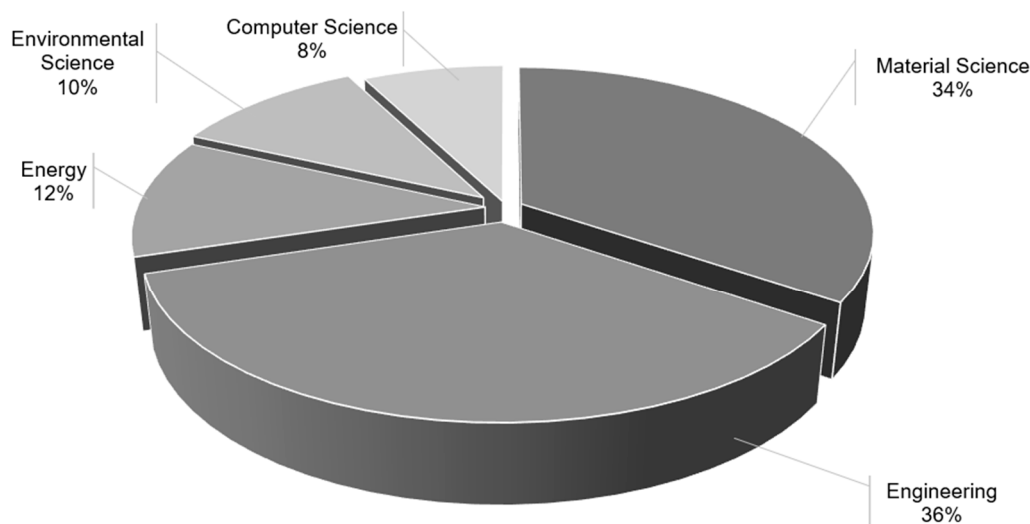
### 2.3. Step 3: Analysis and Evaluation of Search Results

In the third step, the literature search results were validated (a), statistically evaluated, (b) and presented (c):

- Content analysis of given publications using text mining to determine the frequency of keywords,
- Statistical trend function was used to compute linear trend line based on the given publication corpus,
- Graphical presentation of search results.

### 3. Analysis of Recent Research on BIM and ME

Implementation of the first phase of the analysis methodology resulted in more than six million publications collected for the 50 keywords in the period 2007–2020. Relative shares of the publications per science field are presented in Figure 3.

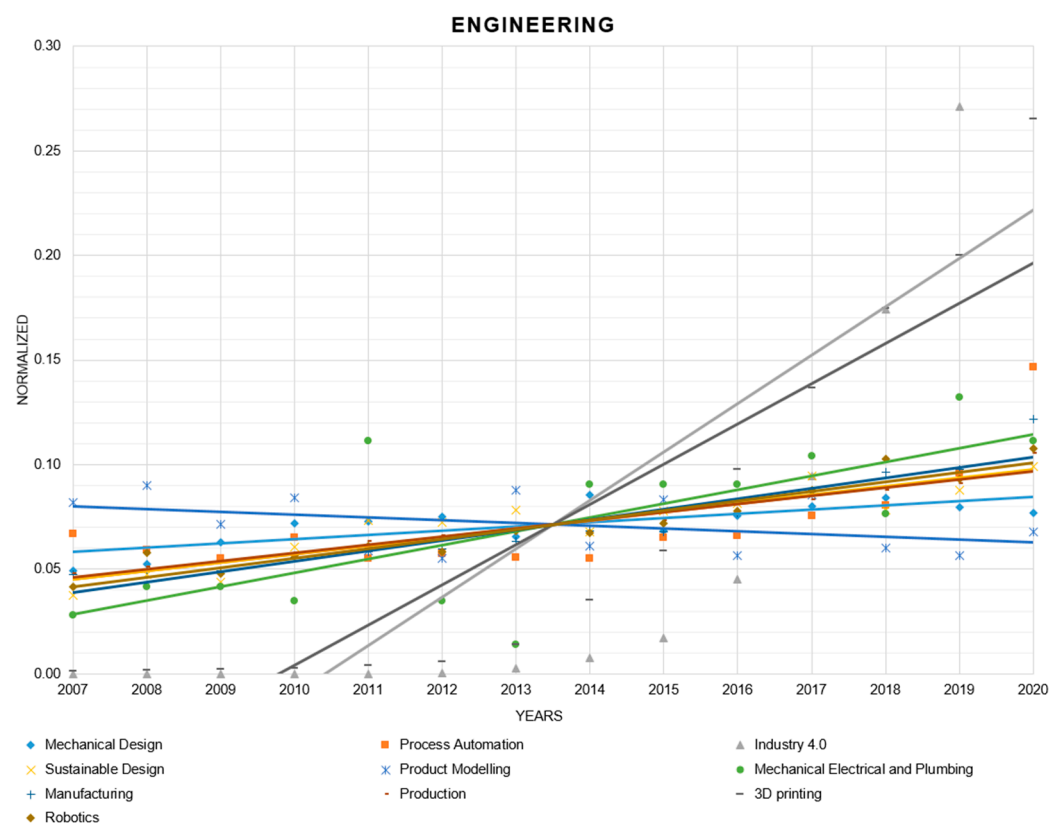


**Figure 3.** Share of ME publications within the science fields comprising AECO.

The absolute number of publications in the search period was normalized and trendlines were calculated separately for the five individual science fields. Figure 4 shows the trendlines for the Engineering field. For each field, the top five trendlines were identified and the corresponding 25 keywords were included in the second phase.

The remaining 25 keywords were all combined with “BIM” (Table 2) in the second analysis phase where 1883 publications were found.





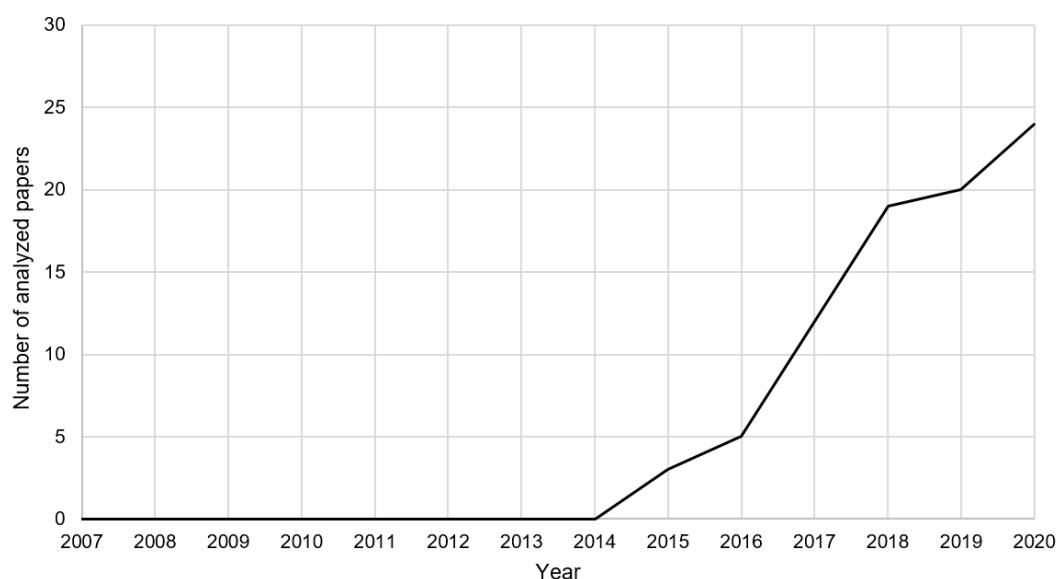
**Figure 4.** Publication trends for the period 2007–2020 for the field of Engineering.

**Table 2.** Keywords for the second phase of review.

Field	Keywords
Material Science	Reinforced material & BIM, Fatigue load & BIM, Construction material & BIM, Nanomaterial & BIM, Mechanical property & BIM.
Engineering	Industry 4.0 & BIM, 3D printing & BIM, Mechanical, Electrical and Plumbing & BIM, Manufacturing & BIM, Robotics & BIM.
Energy	Green energy & BIM, Energy system & BIM, Thermal energy & BIM, Energy efficiency & BIM, Energy optimisation & BIM.
Environmental Science	Environmental Product Declaration & BIM, Lifecycle cost analysis & BIM, Climate change & BIM, Greenhouse gas emissions & BIM, Environmental Design & BIM.
Computer Science	Parametric modelling & BIM, Computational fluid dynamics & BIM, Numerical optimisation & BIM, Geometric optimisation & BIM, Finite element method & BIM.

After the application of the inclusion criteria in the second phase, 91 publications remained. After the elimination of duplicates, 83 publications were selected for the next step. The temporal distribution of the final set of publications is presented in the Figure 5.





**Figure 5.** Temporal distribution of the final set of publications.

The temporal distribution shows a steep rise in the number of publications per year for the final corpus of keywords (Table 2). This supports the state-of-the-art research fields on the intersection of BIM and ME.

The distribution of the 83 papers across the science fields shows the most prosperous research fields and subfields at the intersection of BIM and ME (Table 3). The field of Engineering was identified as the most prosperous one, followed by the fields of Energy, Environmental Science, Material Science, and Computer Science.

**Table 3.** Distribution of the final set of publications for ME and BIM.

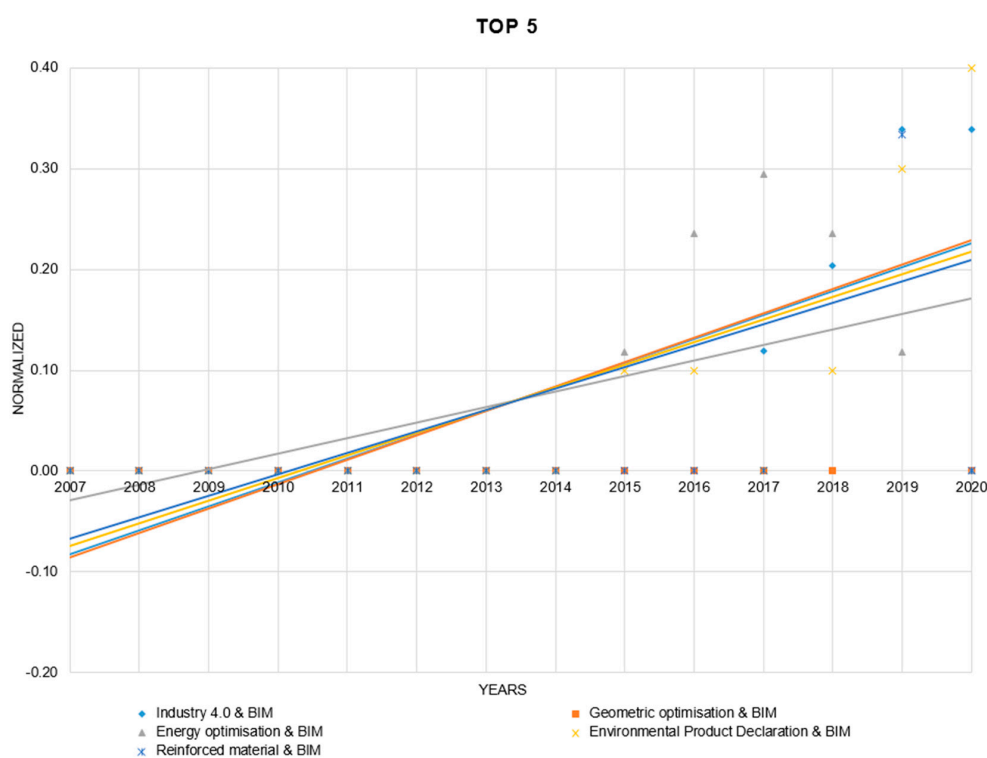
Field	Keywords (Subfield)	Number of Publications
Engineering	Industry 4.0 & BIM	51
Energy	Energy optimisation & BIM	17
Environmental Science	Environmental Product Declaration & BIM	10
Material Science	Reinforced material & BIM	3
Computer Science	Geometric optimisation & BIM	2

However, as shown in Figure 6, the biggest trend is demonstrated by the keyword “Geometric optimisation & BIM”, followed by “Industry 4.0 & BIM”, and “Environmental Product Declaration & BIM”. The year of publication and the number of publications per year has a major impact on the rise of trends.

The structured and mechanistic research method developed for the analysis resulted in a final corpus of 83 scientific publications. In the research step, the full texts of the 83 publications were analyzed with the term frequency analysis tool to determine frequency counts of terms. For text-mining, an algorithm was developed in the R programming language environment [27] to scan the publications in .pdf format. The algorithm disregarded conjunctions and prepositions as these are common words.

By counting the frequency of terms in publications, the stability of the results in terms of the usage of the term “BIM” was validated. Table 4 ranks the top 20 frequencies of terms in all the final publications together.





**Figure 6.** Trends for the final 83 publications.

**Table 4.** Top 20 frequencies of terms for the final corpus of publications.

	Term, Frequency
1.	BIM, 1903
2.	Energy, 1616
3.	Building, 1579
4.	Construction, 1420
5.	Design, 1101
6.	Information, 1051
7.	Model, 1030
8.	Process, 607
9.	Analysis, 490
10.	System, 484
11.	Research, 447
12.	Industry, 427
13.	Optimisation, 427
14.	IFC, 386
15.	Modeling, 382
16.	Environmental, 376
17.	Management, 364
18.	Performance, 345
19.	Project, 345
20.	Consumption, 309



The terms “BIM”, “Energy”, “Building” and “Construction” are the most frequently repeated terms in the final set of papers, followed by the terms “Design”, “Information” and “Models”. The ranking of the term “BIM” as the most frequent confirms its relevance to and its representativeness of the final corpus of publications.

#### 4. Discussion

In this section, a synthesis of research results is analyzed and discussed. The purpose of the synthesis is to assess the stability of results based on the final set of 83 publications (Table 5). During this step, each publication was read (by a researcher) to verify that it considers a BIM approach and also influences ME. Such a contextual approach was crucial in the decision to exclude research with a weak reference to BIM (i.e., pretentious use of “BIM” in the keyword list, presenting BIM as 3D modelling only, etc.), thus contributing to the reliability and relevance of the research publications. Publications with accepted content (title, abstract, keywords, text) were grouped to form 14 subfields of ME that aggregate current research related to both BIM and ME. Based on the synthesis step, the findings are discussed in the next section.

**Table 5.** Most relevant findings with an impact on BIM and ME.

Field	ME Subfield	Application of BIM	Impact on ME
Computer Science	Optimisation and simplification of models	Solid volume optimisation and optimisation of model storage, geometry transfer and visualization [28,29].	Improved interchangeability of detailed MEP models—maintaining a high density of irregularly shaped mechanical components and reduced storage volume.
	Improved material use	Optimisation of rebar quantity [30] and determination of junction points in free form buildings [31].	Improved rebar steel utilization, a transition of knowledge from glass fiber reinforced material to BIM with the purpose of supporting the production.
Material Science	Repairing and retrofitting of products	Implementation of BIM as a data-centric model for current and new assets information [32].	The transition of 3D printing technologies to the field of bridge repairing and retrofitting.
	Sustainable design and development	BIM as a tool for integration of sustainability indicators, digitalization of Life Cycle Analysis (LCA) and decision making in early design phases with respect to environmental impacts [33–40].	Encouraging the sustainable development of mechanical components and integrated subsystems into BE with the LCA approach and minimization of environmental impacts.



Table 5. Cont.

Field	ME Subfield	Application of BIM	Impact on ME
Energy	Optimisation of energy utilization in the production process.	BIM as an emerging technology that supports the energy associated processes [41,42].	New methods for improvement of energy consumption in the production and transport processes of mechanical components and subsystems, intended to be installed in BE.
	Interoperability challenges	BIM as an emerging technology that supports the integration of processes during the product lifecycle, developed as a tool for data transfer between stages in design [43–46]. Adoption and integration of BIM for the optimisation of energy efficiency in the BE, in the design and construction phases, considering the size of the projects and traditional methods [47–55].	Improved data transfer (BIM to BEM) in optimisation processes, reducing software interoperability problems, common also in ME.
	Optimisation of energy efficiency	Automatization of BIM design for mass-customized houses and reconstruction processes of indoor environments [56,57]. Investigations of the impact of BIM-based functions on the construction industry and society [58,59]. Digitalization of BE based on metamodels, augmented reality, digital twins, Internet of Things and Computer Vision [60–76]	Increased need for energy-efficient mechanical components and subsystems.
	Automated design		Minimization of the modelling effort for MEP systems.
	Multidisciplinary connectivity		The necessity for integration of ME in BIM functions.
Engineering	Digitalization		Digitalization of BE in general means also digitalization of ME subsystems, consequently all ME components must be available in an interoperable digital form with integrated information.
	Construction Equipment Industry	Analysis, reviews and case studies of the BIM impact on the development and automatization of the construction industry and its parties [77–93]	
	Product modelling	Implementation of information modelling technologies [94–101].	CAD modelling with respect to requirements of BIM technologies.



Table 5. Cont.

Field	ME Subfield	Application of BIM	Impact on ME
	Additive manufacturing	Application of additive manufacturing technologies in Industry 4.0 and improved material utilization [102–106].	Transfer of knowledge and best practice cases from the field of additive manufacturing to a BE.
	Improved workflow	Combining Industry 4.0 and BIM technologies with the purpose of construction logistics optimisation [107,108].	Chance for the implementation of standardized production layouts from ME industries.

## 5. Conclusions

This paper presented a cross-disciplinary analysis on the influence of BIM on the broad ME domain. Mechanical engineering has long been a major driver of research, applications in product modelling, and data management that improves interoperability between software involved in the product lifecycle. After some time, the construction industry started to adopt and adapt product modelling standards, used during the entire lifecycle of buildings and infrastructures, that evolved into BIM. BIM now has an established influence on the mechanical engineering domain. In this paper, a bibliometric analysis that encompasses the five domains of Environmental Science, Engineering, Material Science, Energy, and Computer Science was performed. For each domain, 10 specific ME related keywords (i.e., “mechanical design”) were defined. Using the keywords, the domains that had gone through a survey method aimed to find relevant evidence for the use of BIM as methodology, methods, and/or products (models). The survey method rigorously implemented a search of relevant publications, a two-phase trend estimation, validation of results, and an assessment of the stability of results. The process started with a set of more than 6 million scientific publications, which at the end were filtered down to 83 publications and systematically analyzed. The distribution of the final publications across the science fields ranked Engineering as the best interwoven with BIM, followed by Energy, Environmental Science, Material Science and Computer Science. The biggest trend was demonstrated by the keywords “Geometric optimisation & BIM” and “Industry 4.0 & BIM”.

The validation of the results, primarily based on the counting of the frequency of the term “BIM” in publications, confirmed that a final analyzed corpus of 83 publications was relevant and representative. The averaged frequencies were ranked solely to prove the occurrence of the term “BIM” in the selected papers, which was confirmed.

To further assess the stability of the results and to develop trust in the relevancy of the research publications, all the 83 publications were also contextually analyzed through reading (by a researcher). The reasoning process derived from the list of the final 11 research fields (Table 5) is the basis for the conclusions that highlight the most researched bidirectional effects between BIM and ME domain, but also identify research opportunities at the crossroads of BIM and ME, particularly:

1. Detailing, optimisation, simplification, and interchangeability of MEP models with requirements for high density of irregularly shaped solid volumes can be better achieved with BIM modelling and IFC-based model exchange.
2. Improved rebar steel utilization through the optimisation of rebar quantity, the determination of junction points in free form buildings, and a transition of knowledge from glass fiber reinforced material to BIM to support the manufacturing phase.
3. Implementation of BIM as a data-centric model for asset information to support the transition of knowledge and best practice cases from 3D printing technologies to the field of bridge repairing and retrofitting.



4. BIM as a tool for the integration of sustainability indicators, digitalization of LCA, and decision making in early design phases with respect to the environmental impacts for the sustainable development of mechanical components and integrated subsystems into BE.
5. BIM is a technology that supports new methods for improvement of energy consumption in the production and transport processes of mechanical components and subsystems intended to be installed in BE.
6. Custom BIM-based tools improve data transfer (BIM to BEM) in the optimisation processes, between design stages during the product lifecycle, and reducing software interoperability problems that are also common in ME.
7. Adoption and integration of BIM improves the optimisation of energy efficiency in the design and construction phases for energy-efficient mechanical components and subsystems when compared to traditional methods.
8. BIM minimizes the modelling effort of MEP systems for mass-customized houses and the reconstruction processes of indoor environments.
9. Digitalization of BE also means implementation of information modelling technologies for ME subsystems where CAD modelling is subordinated to the requirements of BIM technologies.
10. Industry 4.0 can benefit from pairing BIM technologies and modularized production layouts from ME industries in the domain of the construction site and in logistics optimisation.
11. Mechanical engineers need to analyze, review, and elaborate on case studies focused on the impact of BIM on the development and automatization of the BE industry.

From the above conclusions, an important consideration for ME to adopt BIM is the concept of design integration between the already “BIMified” disciplines and ME. As conclusions 1, 2, 3, and 9 suggest, an obstacle to BIM is information loss which occurs during the repetitive exchange of digital information taking place throughout the design and analysis activities (e.g., BIM to energy analysis) until all design requirements are met. That calls for improved algorithms that can integrate several mono-discipline models into one, a concept known as an integrated model, and is also applicable to federated models. Conclusions 3, 4, 8, and 10 also call for better-integrated design (requirements, models) in automated manufacturing workflows, including digital fabrication. That all must be underpinned by mechanical engineers with competencies for BIM projects as described in conclusion 11.

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