CivilEng

Review

Building Information Modelling in Structural Engineering: A Qualitative Literature Review

Vittoria Ciotta *, Domenico Asprone, Gaetano Manfredi and Edoardo Cosenza

Department of Structures for Engineering and Architecture, University of Naples Federico II, 80125 Naples, Italy; d.asprone@unina.it (D.A.); gaetano.manfredi@unina.it (G.M.); edoardo.cosenza@unina.it (E.C.)
* Correspondence: vittoria.ciotta@unina.it

Abstract: Over the past decade, the fields of civil engineering, i.e., structural engineering, have increasingly used the building information modelling (BIM) approach in both professional practice and as the focus of research. However, the field of structural engineering, which can be seen as a sub-discipline of civil engineering, misses, as far as the authors are aware, a real state-of-the-art on the use of BIM in this regard. The aim of this paper, therefore, is to start bridging that gap. In particular, the authors have conducted a traditional literature review on the utilisation of BIM in structural engineering, enabling them to perform a detailed content analysis of publications. The qualitative investigation of the literature that the authors have conducted has highlighted six main BIM uses in structural engineering: (1) structural analyses; (2) production of shop drawings; (3) optimized structural design, early identification of constructability issues, and a comparison of different structural solutions; (4) seismic risk assessments; (5) existing-condition modelling and retrofitting of structures; and (6) structural health monitoring. Each of these is discussed in relation to their reference workflows; use of information models; information exchanges; and main limitations. In the conclusions, the authors identify current gaps in knowledge, as well as likely developments and improvements in the utilization of BIM in structural engineering. The authors also outline the possible significance of this work more broadly.

Keywords: BIM; structural engineering; traditional literature review; structures; structural design; structural analysis; existing structures; structural health monitoring; structural damage assessment; seismic risk assessment

check for updates

Citation: Ciotta, V.; Asprone, D.; Manfredi, G.; Cosenza, E. Building Information Modelling in Structural Engineering: A Qualitative Literature Review. *CivilEng* **2021**, *2*, 765–793. https://doi.org/10.3390/civileng2030042

Academic Editors: Angelo Luongo and Francesco D'Annibale

Received: 27 April 2021
Accepted: 31 August 2021
Published: 4 September 2021

1. Introduction

The building information modelling (BIM) approach fosters collaboration between the stakeholders in a project. It also uses the unique sources of data available in multidisciplinary, integrated, verifiable, and updatable information models to streamline the exchange of information [1]. Moreover, BIM-based workflows, innovative tools, and collaboration platforms can be employed throughout the lifecycle of an asset [2], and have been the catalyst for innovation in the entire architecture, engineering, and construction (AEC) industry [3]. Over the past decade, the BIM approach has increasingly been used in both professional practice and research relating to the fields of civil and structural engineering. Indeed, it has been adopted across the globe [4], with some governments demanding its use in public projects involving bridges, tunnels, and railways, as well as for strategic facilities such as hospitals and schools. In Europe, most countries comply with *Directive 2014/24/EU of the European Parliament and of the Council* [5] on public procurements, which allows such clients to demand the use of BIM methodologies. Some countries, meanwhile, have decided to enforce digital delivery; for example, the United Kingdom has required the use of BIM in all government projects since 2016, while the Italian government published a timeline in 2018 mandating the use of BIM methodologies in all construction work by 2025. As a consequence, companies involved in the AEC sector are embracing the BIM approach by employing new tools and workflows, even though they face obstacles in relation to issues such as training costs and time or low initial productivity [6]. The focus of academic research on the benefits and limitations of the BIM approach in the production of construction deliverables for new buildings [7,8] has also evolved in the last decade. The emphasis is now on potential new uses, as well as interoperability issues between BIM-authoring software and that used in finite element analyses (FEA) to conduct structural assessments [9–12]. It is worth noting that the current trend in relation to existing buildings is orientated towards employing the accurate and reliable information management and visualization processes of information models to improve structural refurbishment and retrofit interventions [13,14]. The use of these models as high-performing repositories has paved the way for a completely new research field that combines their benefits with the advantages of diagnostic approaches such as structural health monitoring (SHM) [15]. However, as far as the authors are aware, there is currently no real state-of-the-art available for consultation on the use of BIM in structural engineering, and so the goal of this paper is to fill this gap. To this end, the authors have conducted a traditional literature review and a qualitative analysis of publications' contents. It is worth noting that the bibliometric review by Vilutiene et al. (2019) [16] is the only relevant example of similar research, even though this is more a quantitative literature review. In detail, the authors have identified six main uses of BIM tools and methodologies in structural engineering. Each of these is discussed in relation to their: reference workflows; use of information models; information exchanges; and main limitations.

The paper has four sections. Section 2 introduces the BIM approach to assist those who are unfamiliar with its methodologies and tools, while Section 3 describes the methodology that the authors have adopted to collect and analyze the information used to produce reference bibliography. Section 4 contains the discussion and is where the authors both present structural engineering's current contemporary experience in relation to BIM and highlight its key limitations. In Section 5, the authors discuss their work in terms of its aims and methodology. Section 6 is the final part of the paper and is where the authors set out their conclusions, identify current gaps, address likely developments and improvements in the use of BIM in structural engineering, and outline the possible significance of this work more broadly.

2. Introduction to the BIM Approach

The National BIM Standard-United States (NBIMS-US) defines BIM as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception onward". According to the authors, this definition could be better understood after addressing three key concepts that relate to information modelling and management:

- Information models.
- Informative processes (workflows).
- Collaboration platforms (common data environments).

Informative processes in the form of workflows are used to develop an information model of an asset throughout a project, ensuring the coherence and accuracy of the data stored in it. A model's contents change and expand during an asset's lifecycle. However, a collaboration platform enables all the stakeholders involved in a project to work together in the same environment using the information stored in such a model. Each key concept is described in detail below.

2.1. Information Models

An information model is created with BIM-authoring software. This is able to sculpt 3D parametric objects that contain many kinds of data, including on costs, mechanical properties, and thermal characteristics. Suitable BIM tools can be used to process the information stored in these models to support tasks such as quantity take-offs, economic estimates, and structural and thermal analyses. An information model can also take the form of several models merged in a centralized and integrated version known as a federated model [1]. In this scenario, each model is typically produced by different project teams from disciplines such as architecture; structural engineering; mechanical; electrical and plumbing (MEP) systems; and heating, ventilation, and air conditioning (HVAC).

2.2. Informative Processes: Workflows

Information models enable the storage of information from all of the disciplines involved in a project. However, it is essential to define well-conceived processes to ensure that these data are consistent and coherent [17]. The BIM approach tackles this by employing standardized work processes instead of stakeholder interactions, and it also supports codified information exchanges by way of both proprietary and open-format software. An explanatory process based on an information model therefore produces standardized and streamlined information flows in relation to the following components:

- The information requirements based on project goals.
- The stakeholders involved.
- The activities to be developed.
- The outputs to be delivered.

Of course, the definitions of these elements differ based on the goals. Furthermore, as the BIM approach can be used throughout the lifecycle of an asset, its processes start from the design phase and foster the integration of information from different disciplines. As an example, the reliability of a model's information relating to 3D coordination, clash-detection, modelling, and code-checking can be tested automatically throughout a project's lifecycle using specific BIM tools. These are computerized and sophisticated ways of performing activities that were once conducted using only the human eye. Moreover, because information models are virtualizations rather than simply representations, the creation of design outputs such as shop drawings, schedules, and bills of quantities is supported by automatic updating procedures. Finally, due to the high quality of the information they store, information models can be used in the facility management phase, as well for maintenance, monitoring, and decision-making.

2.3. Collaboration Platforms

Collaboration platforms are local or cloud environments with access rules and privileges for each stakeholder; they are also where project documentation (information models, structural analysis models, reports, documents, schedules, plans, etc.) is stored. Known worldwide as a common data environment (CDE), the ISO 19650 series of standards defines the requirement to use a CDE to collect, manage and disseminate information during BIM projects. Consequently, a collaboration platform supports BIM processes and underpins collaborative approaches. Current CDE solutions facilitates a dynamic environment where 'information containers' [18,19] (i.e., project documentation) move between different stages based on a particular workflow. An information container normally starts with a *work-in-progress* stage, before moving to a *shared* stage. The *published* stage is achieved after several exchanges back and forth between the first two phases. The final step occurs when the information container is *archived*. Moving from one stage to the next requires the deployment of a process consisting of checks, approvals, and authorizations. In this regard, CDE solutions today all contain valuable tools for use in process design and management.

2.4. A Brief Introduction to openBIM®

The Institution of Civil Engineers (ICE) defines interoperability as 'the ability of computer systems or software to exchange and make use of information' [20]. In the BIM approach, stakeholders generally choose their tools according to internal necessities rather than collaboration criteria, meaning that informative processes often deploy software that is produced by different software houses. Commonly, a software house always ensures the interoperability of its own products. Those by different vendors can become interoperable with plug-ins, which software houses use to collaborate to ensure the compliance of products with vendor-neutral formats such as IFC, PDF, BCF, COBie, CityGML, gbXML, and .cvs. In this regard, buildingSMART International not only fosters the diffusion of openBIM®, "a collaborative process that is vendor-neutral" [21], but also develops and maintains openBIM® industry standards such as IFC, IDM, bSDD, and BCF. For the sake of brevity, and to facilitate the reader's understanding of the sections that follow, a brief introduction to IFC and IDM is set out below.

The Industry Foundation Classes (IFC) format is an open, vendor-neutral data model schema that is currently standardized in ISO 16739-1:2018 [22], while the Information Delivery Manual (IDM) is a methodology which aims to "*facilitate interoperability between software applications used in the construction process, promote digital collaboration between actors in the construction process and provide a basis for accurate, reliable, repeatable and high quality information exchanges*" [23]. The IDM methodology is currently standardized in ISO 29481-1:2016 [23] and ISO 29481-2:2012 [24] and includes process maps, interaction maps, and exchange requirements. A process map describes the sequence of activities within a particular topic, the stakeholders' roles, and the information required, created, and consumed [25]. An interaction map defines roles and transactions for a specific purpose, while exchange requirements identify a "*set of information that needs to be exchanged to support a particular business requirement*" [23]. This information exchange is based on the IFC format, via the IFC model view definition format (MVD), which is a subset of the IFC schema needed to satisfy one or many exchange requirements. Various MVDs have been certified by buildingSMART®, for example, the Coordination View; the Structural Analysis View; the Basic FM Handover View; the Space Boundary Add-on View; and the Reference View [26]. These are already on the list of MVD options available in the IFC export user interfaces of BIM-authoring software, but there is also an opportunity to develop new MVDs.

3. Methodology

The methodology adopted to develop this qualitative literature review on the use of BIM in structural engineering both in industry and research had three key steps:

1. A traditional literature search on the use of BIM in structural engineering. This has enabled a thorough analysis of the content uncovered in order to identify: (1) the topics addressed by relevant publications pertaining to structural engineering (i.e., structural analyses, structural type, structural design, damage assessment, performance-based earthquake engineering (PBEE), post-earthquake assessments, SHM, etc.); (2) the phase(s) of a building's lifecycle considered by these publications; and (3) the availability of reference BIM workflows (or process maps).
2. A qualitative analysis of the content relating to structural engineering uncovered in Step 1. This highlighted six main areas where BIM tools and methodologies are used in structural engineering, i.e., 'BIM uses in structural engineering'. These six uses are described in detail to follow; additionally, the outputs of a comparison of these six uses with the '25 BIM uses' documentation produced by Penn State University is presented. In this regard, the authors defined three matching criteria in relation to the list of BIM uses and their description given in the Penn State University guide:
    - Weak: there is no BIM use with the same title proposed by the authors nor is there a BIM use that, in its description, focuses on the structural engineering area that the authors identified.
    - Medium: there is either a BIM use with the same title identified by the authors or there is a BIM use (or more than one) that focuses on the same topic proposed by the authors, even if the description in the guide is too general and never directly relates to the structural engineering discipline.
    - Strong: there is a BIM use with the same title identified by the authors and its description goes into detail about the structural engineering area that the authors identified.

3. A detailed description of the identified BIM uses in structural engineering, highlighting their reference workflows in contemporary experience, use of information models and information exchanges, and their main limitations.

Literature Search on the Use of BIM in Structural Engineering

Search engines such as Google Scholar, Scopus, and ASCE were used to conduct a literature search for articles, conference reports, and books relating to BIM and structural engineering concurrently. After a preliminary analysis of the title, keywords, and abstract, many papers were excluded from any further analysis, because their focus was mainly on disciplines such as architecture, energy performance, and sustainability, or their purpose was to explain the BIM strategies adopted by construction companies, engineering firms, and educators. Some of these studies may, nonetheless, be valuable for those wanting a comprehensive literature review on the BIM approach more generally [27,28]. However, papers with mixed topics were considered where this preliminary analysis highlighted relevant structural engineering content. The authors' final bibliography references 45 journal articles, conference reports, and books, and is summarized in Table 1 below.

Table 1. Results of literature search on the use of BIM in structural engineering.

Reference	Year	Type of Publication	Structural Engineering Content	Building Lifecycle				BIM Content		
				Plan	Design	Construct	Operate	Is There Any BIM Workflow or Process Map in This Publication?	Is Integration with One or More Disciplines Addressed?	Is Interoperability Addressed in This Publication?
[29]	2012	Journal article	Structural safety; structural analyses; comparison of different structural design solutions (set-base analysis); early-stage optimization of structural design choices with respect to constructability criteria (cost-estimations and quantity take-offs); outrigger systems (high-rise buildings).		X			Yes	Yes	Yes
[30]	2014	Conference paper	Structural safety; structural analyses.		X			No	Yes	Yes
[31]	2015	Journal article	Structural analyses; structural design optimization; early-stage optimization of structural design choices with respect to constructability criteria.		X			Yes	No	No
[32]	2016	Journal article	Structural analyses.		X			Yes	No	Yes
[9]	2016	Conference paper	Structural analyses; bridge engineering.		X			Yes	No	Yes
[33]	2017	Journal article	Structural analyses; BIM collaboration processes in structural engineering.		X	X		No	Yes	Yes
[10]	2016	Journal article	Non-linear FEM analysis; structural analyses; lifecycle reliability of structures and structural elements; concrete and reinforced concrete structures; bridge engineering.		X			Yes	No	Yes
[11]	2018	Journal article	Structural analyses.		X			No	No	Yes
[34]	2018	Conference paper	Structural analyses.		X			No		Yes
[35]	2018	Book	Structural design; structural analyses; production of structural engineering deliverables from structural building information modelling (S-BIM).		X	X		Yes	Yes	Yes
[12]	2019	Journal article	Structural analyses.		X			No	No	Yes
[7]	2009	Journal article	Production of structural engineering deliverables; optimization of structural design choices on constructability criteria; pre-cast concrete; pre-stressed concrete; structural engineering.		X	X		No	Yes	Yes
[1]	2012	Book	Production of structural engineering deliverables from S-BIM.		X	X	X	No	Yes	Yes
[36]	2009	Journal article	S-BIM; fabrication model; precast concrete; steel and cast-in place reinforced concrete members.		X	X		No	Yes	Yes
[37]	2011	Journal article	4D structural information model; time-dependent structural models; structural analyses; optimization of structural design choices on safety criteria.		X	X		Yes	Yes	Yes

Table 1. *Cont.*

Reference	Year	Type of Publication	Structural Engineering Content	Building Lifecycle				BIM Content		
				Plan	Design	Construct	Operate	Is There Any BIM Workflow or Process Map in This Publication?	Is Integration with One or More Disciplines Addressed?	Is Interoperability Addressed in This Publication?
[38]	2011	Journal article	4D structural information model; time-dependent structural models; structural analyses; optimization of structural design choices on safety criteria.		X	X		Yes	Yes	Yes
[39]	2016	Journal article	Early-stage optimization of structural design choices on constructability criteria.		X	X		Yes	No	No
[40]	2012	Journal article	Early-stage optimization of structural design choices on economic criteria.		X	X		Yes	No	No
[41]	2013	Journal article	Quantity take-off-oriented BIM-based design; optimization of structural design choices.		X			Yes	No	No
[42]	2015	Journal article	Early-stage optimization of structural design choices on quantity take-off criteria.		X			Yes	No	No
[43]	2010	Journal article	Pacific Earthquake Engineering Research (PEER) Centre's performance-based earthquake engineering (PBEE) methodology; assembly-based vulnerability (ABV); damage analysis; structural and non-structural components; scheduling of 3D/4D visualizations for post-earthquake building rehabilitation.		X			Yes	No	No
[44]	2014	Journal article	Seismic risk assessment; seismic risk mitigation; PEER Centre's PBEE methodology; damage analysis assessment; existing structures; structural and non-structural components; structural health monitoring; post-earthquake inspections.		X		X	No	No	No
[45]	2017	Journal article	PBEE; automated seismic design; FEMA P-58 method; structural and non-structural components.		X			Yes	No	No
[46]	2016	Journal article	Existing structures; post-earthquake damage assessment; strength analysis; reinforced concrete.				X	Yes	No	No
[47]	2016	Conference paper	PBEE; structural analyses; earthquake-loading conditions; damage analysis; lifecycle environmental assessment (LCA); environmental impact of damaged building; seismic retrofit.		X		X	Yes	No	No
[48]	2019	Journal article	PBEE; FEMA P-58 method; seismic loss assessment; structural and non-structural components.		X			No	No	No

Table 1. *Cont.*

Reference	Year	Type of Publication	Structural Engineering Content	Building Lifecycle				BIM Content		
				Plan	Design	Construct	Operate	Is There Any BIM Workflow or Process Map in This Publication?	Is Integration with One or More Disciplines Addressed?	Is Interoperability Addressed in This Publication?
[49]	2020	Journal article	Seismic risk assessment; non-structural elements.		X			Yes	No	No
[14]	2019	Journal article	PEER Centre's PBEE methodology; lifecycle costing (LCC); optimization of seismic retrofit strategies; damage analysis; structural and non-structural components; existing structures.		X		X	Yes	No	No
[50]	2019	Journal article	Seismic structural analysis; seismic damage simulation and analysis; octree algorithm for discretization; complex geometries.		X			Yes	No	No
[51]	2015	Journal article	Existing structures; building condition assessment (structural survey); as-built modelling of structures; access to and integration of maintenance information and knowledge.				X	No	No	No
[52]	2015	Journal article	Existing structures; building condition assessment (structural survey); as-built modelling of structures; finite element analysis (FEM); structural analysis; complex geometries.				X	Yes	No	No
[53]	2016	Journal article	Existing structures; building condition assessment (structural survey); as-built modelling of structures; structural analysis; timber roof structures; complex geometries.				X	Yes	No	No
[54]	2017	Journal article	Existing structures; building condition assessment (structural survey); structural analysis; seismic vulnerability.				X	Yes	No	Yes
[13]	2018	Journal article	Existing structures; building condition assessment (structural survey); management of diagnostic tests; structural analysis; diagnostics and monitoring for structural reinforcement.				X	Yes	No	No
[55]	2018	Journal article	Existing bridges; reinforced concrete bridges; defect modelling.				X	Yes	No	Yes
[25]	2014	Journal article	Existing structures; building condition assessment (structural survey); retrofitting.				X	Yes	Yes	Yes
[56]	2017	Journal article	BIM-based bridge management system; bridge maintenance; inspection system using 3D models; existing cable-stayed bridge.				X	Yes	No	No
[57]	2019	Conference paper	Existing structures; building condition assessment (structural survey); as-built modelling of structures; management of diagnostic tests.				X	No	No	No

Table 1. *Cont.*

Reference	Year	Type of Publication	Structural Engineering Content	Building Lifecycle				BIM Content		
				Plan	Design	Construct	Operate	Is There Any BIM Workflow or Process Map in This Publication?	Is Integration with One or More Disciplines Addressed?	Is Interoperability Addressed in This Publication?
[58]	2015	Conference paper	Structural health monitoring (SHM); as-built modelling of infrastructures; existing infrastructures.				X	No	No	Yes
[59]	2017	Conference paper	SHM; modelling of structural performance monitoring systems; pre-stressed concrete bridge.				X	No	No	Yes
[60]	2017	Conference paper	SHM; modelling of structural performance monitoring systems.				X	No	No	Yes
[15]	2017	Conference paper	SHM; archiving and visualizing SHM data; existing bridges.				X	Yes	No	No
[61]	2018	Journal article	SHM; bridges.				X	Yes	No	Yes
[62]	2018	Journal article	SHM; damage visualization.				X	Yes	No	Yes
[63]	2018	Journal article	SHM; modelling of structural performance monitoring systems.				X	No	No	Yes

4. Results

Table 1 presents the results of the literature search on the use of BIM in structural engineering and the authors' analysis of the content uncovered. The final bibliography references 45 journal articles, conference reports, and books.

The authors conducted a thorough analysis of the content uncovered in these 45 publications in order to identify:

- Topics pertaining to structural engineering (i.e., structural analyses, structural type, structural design, damage assessment, PBEE, post-earthquake assessments, SHM, etc.) addressed in the publications.
- The building lifecycle phase(s) considered.
- The BIM content of the publications was analyzed from a methodological and technological perspective. In the first case, the authors identified the availability of reference BIM workflows (or process maps) by answering the question: 'is there any BIM workflow or process map in this publication?'. In addition, the authors highlighted the possible collaborative characteristic of the implemented processes by answering the question: 'is integration with one or more disciplines addressed?'. From a technological perspective, the authors preferred to neglect details about the technologies used in the publications. However, the authors highlighted whether a publication specifically addressed interoperability (and issues that may be related to this) among the implemented technologies by answering the question, 'is interoperability addressed in this publication?'

The year and type of publication are also specified.

4.1. The BIM Approach in Structural Engineering: The Main BIM Uses

The authors' qualitative analysis of the structural engineering content described in Table 1 identified six main areas in the field where BIM tools and methodologies can be employed, i.e., BIM uses:

(1) Structural analyses.
(2) Production of shop drawings.
(3) Optimized structural design: early identification of constructability issues and comparison of different structural solutions.
(4) Seismic risk assessments.
(5) Existing-condition modelling and retrofitting of structures.
(6) Structural health monitoring.

The term 'BIM use' was first coined in 2013 by Penn State University, which defines it as a unique task or procedure on a project which can benefit from the integration of BIM into that process [64]. Although only some of the publications summarized in Table 1 address the employment of the BIM approach throughout a project, all of those listed aimed to both describe the integration of BIM tools and methodologies in very specific aspects (or purposes) of structural engineering and explain the benefits and limitations of the BIM approach. Table 2 sets out a detailed account of six BIM uses that the authors identified, clarifying the ways in which the methodology can be applied in structural engineering. The table also includes a comparison with the list of 25 BIM uses contained in the BIM Project Execution Planning Guide [64]. This reveals strong correspondence for BIM use (1) medium correspondences for (2), (3), and (5), and weak correspondence for (4) and (6). The medium correspondences originate from the broad nature of the BIM use descriptions produced by Penn State University and from the absence of any reference to the structural engineering discipline. Meanwhile, the weak correspondences for BIM uses (4) and (6) originate from the very specific structural engineering functions of these BIM uses.

We have also considered the possibility of similarly referring to the specific 'Model Uses' defined by Succar et al. as a way 'to identify and collate the Information Requirements that need to be delivered as—or embedded within—3D digital models' [65]. Unfortunately, most of the publications in Table 2 fail to identify clear information requirements, with their focus instead mainly on workflows and interoperability; this makes it very difficult to distinguish any specific model uses. The authors have identified applications described in Succar's general and domain lists of model uses that could relate to structural engineering: from the former—brick structure modelling, concrete structure modelling, timber structure modelling, and steel frame modelling; and from the latter—2D documentation, finite element analyses, structural analyses, and wind studies [65].

Table 2. Detailed description of the authors' BIM uses in relation to structural engineering and a comparison with those of Penn State University.

	Authors' Six BIM Uses	Description of BIM Use in Relation to Structural Engineering	Correspondence with Penn State's BIM Uses
(1)	Structural analyses.	A structural analysis is the method used by structural engineers to assess the structural behavior of structures under different load conditions. It is typically performed following the concept structural-design stage, and so materials and geometries are broadly assigned [35]. If a structural information model is available after the design stage, a structural analytical model can be generated from it and exported to computational software in order to define the FEM and conduct the structural analyses [64]. The quality of this export-import operation depends on the interoperability of the BIM-authoring and computational software used.	Strong correspondence with (13)—Engineering Analysis—b. structural analysis.
(2)	Production of shop drawings.	The structural solution designed and verified by the structural engineer is typically translated into 2D representations dubbed shop drawings. The use of BIM-authoring software enables this step to be automated (or at least, semi-automated), because shop drawings can be derived from a structural information model, if one is available. Concurrently, the model is used to perform clash detections with respect to other disciplines, meaning that there is high-level integration among project disciplines and time-consuming rework activities are also avoided.	Medium correspondence with (11) 3D coordination, and (12) Design authoring.
(3)	Optimized structural design: early identification of constructability issues and comparison of different structural solutions.	The construction of the structural solution designed by the structural engineer is typically an issue of construction engineering. However, some products such as bridges and other complex designs (e.g., tall buildings or buildings with unconventional geometries) are greatly affected by the construction process identified in the design stage. In addition, these kinds of structure are commonly composed of highly industrialized (and often unique) structural elements made of pre-cast reinforced concrete, pre-stressed reinforced concrete, and steel. Structural engineers maintain communication with manufacturers and suppliers to address production issues with such structural elements [31]. In this regard, the BIM approach allows the definition of procedures for sharing information with manufacturers right from the start of the design process [66]. Indeed, a structural information model can be both exchanged and used concurrently to manage scheduling, material quantities and costs. In this way, different structural solutions exchanged with manufacturers can be compared in terms of their construction time and cost, thus optimizing project choices in the design stage.	Medium correspondence with (8) Construction system design, (19) 4D modelling and (20) Cost estimations.

Table 2. *Cont.*

Authors' Six BIM Uses		Description of BIM Use in Relation to Structural Engineering	Correspondence with Penn State's BIM Uses
(4)	Seismic risk assessments.	The seismic load is considered in general structural analyses, but more sophisticated methods are needed when it comes to the assessment of the damage state of structural and non-structural components and any resulting losses [44]. Performance-based earthquake engineering (PBEE) is one of these methods. Structural and non-structural components are all included in a (probably federated) information model. This can therefore be used as a repository of inputs to support the PBEE (and other sophisticated analysis methods such as LCAs and LCCs for sustainability assessments). Additionally, the results of these sophisticated computations can be stored in information models, potentially improving visualizations and communication with non-experts.	Weak correspondence with Penn State's BIM uses. This can be explained because seismic risk assessment is a specific purposes of structural engineering discipline.
(5)	Existing conditions modelling and retrofitting of structures.	Existing conditions modelling of structures represents a stand-alone scope, since there is no design stage and no integration among disciplines; instead, only fragmented information is available [25]. A structural survey is required in most cases and can be performed using in-situ techniques such as photogrammetry and 3D laser-scanning. After an elaboration stage, a point cloud from images and scans is imported into a BIM-authoring environment, thereby establishing the pathway upon which the 3D digital model is built. A structural analytical model is then generated and exported to computational software in order to define the FEM and perform the structural analyses. However, further in-situ and laboratory tests are needed to define the mechanical properties of structural materials [57]. Information models and collaborative platforms enable sharing and management of all sources of information that come into play in relation to existing structures. These, thus, provide a shared and reliable source of information to perform structural performance assessments and retrofit design.	Medium correspondence with (21)—Existing conditions modelling. There is no mention of structural performance assessments and retrofit design.
(6)	Structural health monitoring.	Information models are used as repositories supporting SHM in relation to the modelling and visualizing of structural-performance monitoring systems and managing and visualizing monitoring data [44]. In more detail, 3D digital models for SHM are enriched with BIM objects representing the sensor-monitoring system and contain a set of informative attributes. Data interpretation and analyses are enabled by purposely developed tools, making them a valuable and reliable way to obtain information for use in decision-making processes concerning refurbishment and maintenance interventions [61].	Weak correspondence with (1)—Building (preventative) maintenance scheduling. There is no mention of structural health monitoring.

Finally, Table 3 contains a tabular organization of the authors' reference bibliography based on the six BIM uses identified earlier. The number of documents considered and their references in the bibliography are also reported, although each document may relate to more than one BIM application.

Table 3. Organization of the reference bibliography according to the six identified BIM uses.

Authors' Six BIM Uses		Number of Reference Documents	Bibliography Reference
(1)	Structural analyses.	11	[9–12,29–35]
(2)	Production of shop drawings.	4	[1,7,35,36]
(3)	Optimized structural design: early identification of constructability issues and comparison of different structural solutions.	9	[1,7,36–39,41,42]
(4)	Seismic risk assessments.	9	[14,43–50]
(5)	Existing conditions modelling and retrofitting of structures.	9	[13,25,51–57]
(6)	Structural health monitoring.	8	[13,15,58–63]
	Total number of articles, papers and books considered.	45	

4.2. Presenting the Main BIM USES in Structural Engineering

In this section, the BIM uses identified in Table 2 are described in detail to present contemporary experience in relation to the use of BIM tools and methodologies in structural engineering.

4.3. BIM Use (1): Structural Analyses

Figure 1 portrays the reference workflow for the BIM use (1), in relation to which the authors refer to the process map of BIM use (13) in the *BIM Project Execution Planning Guide* [64] because of the strong correspondence between this BIM use and BIM use (1).

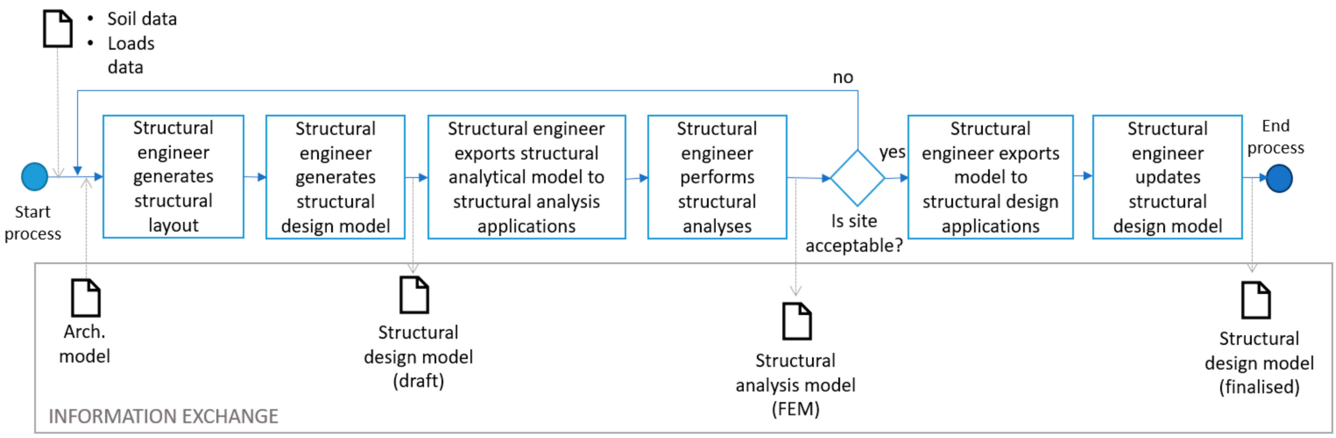

Figure 1. Reference workflow of BIM use (1)—structural analyses.

In detail, the process starts with a concept design of the load-bearing structure, which provides an architectural information model and inputs the foundation soil and loading conditions. In the next step, structural engineers create a draft structural information model; this is then used to define a structural analytical model [35] that can be exported for any following structural analysis applications. These are able to perform FEA calculations on the structural analytical model, which is converted into a FEM (see Figure 2). Consequently, the structural engineers have to make a decision: if they detect issues with the site conditions (as well as with the compatibility with the architectural model), they can demand substantial changes that could involve the design concepts of both the structural and architectural models. Accordingly, in these circumstances, the entire process would be repeated, as depicted in Figure 1. If no issues are highlighted, the structural design can be completed. This is achieved using post-processing plug-ins or suitable applications with which to complete the ultimate structural design (according to the reference standard) in relation to the structural member assessments, reinforcements and connections [29].

The final step involves updating the structural information model, bringing the process to an end.

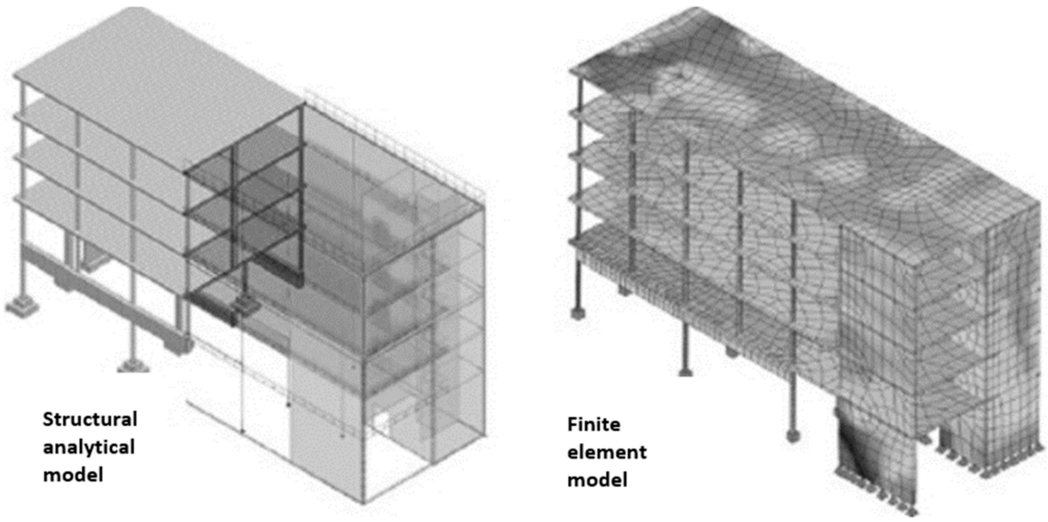

Figure 2. Structural analytical model of an office building and the finite element mesh generated from it [35].

However, significant reworking may be required to set the FEM up correctly for the structural analyses; this is because interoperability issues can arise [33], creating a need for further inputs (i.e., the reference standard) [30,32]. These issues can slow the process down significantly, and so are analyzed in more detail in Section 4.3.1 below.

4.3.1. Limitations

Interoperability issues between BIM-authoring and FEA software are common, meaning that much of this discussion is dedicated to analyzing this limitation. Developing a structural analytical model from its BIM counterpart, and then importing it into FEA software to produce a FEM, can be achieved by adopting proprietary format plug-ins, if available, which enable information exchanges between BIM-authoring and FEA software [32,67,68]; and openBIM® standards, which involve using the IFC format to support the information exchanges [28,69]. In such cases, any BIM-authoring and FEA software that allows exports–imports of the IFC format to be used.

A structural analytical model should include:

- Geometry and sections of structural members (i.e., beams, columns, walls, and slabs).
- Materials assigned to structural members.
- Loads (it is worth noting that BIM-authoring software is unable to manage reference standards for structural engineering. Therefore, while structural analytical models can include gravity loads such as destination use and the weight of non-structural components, they fail to contain load types such as wind or seismic action and load combinations in general).
- Constraints (i.e., fixed joint constraint, hinge joint constraint, etc.).

Minor interoperability issues have been detected adopting proprietary format plug-ins. These have been widely investigated in [9,11,12], and arise because plug-ins are specifically developed (mainly by software vendors and developers themselves) to ensure that the FEA software interprets the structural analytical models correctly on a semantic level (semantic interoperability is '*the ability of two tools to come to a common understanding of the meaning of a model being exchanged*' [70]). Commonly, plug-ins are available when the BIM-authoring and the FEA software are from the same software house, or if two different houses work together to develop a solution to achieve semantic interoperability. In addition, these allow round-tripping exchanges in relation to the geometry and sections of the structural elements.

Using openBIM® standards is affected by major interoperability issues. This is because exchanges of data between the BIM-authoring and the structural analysis software using the IFC format can be affected by inaccuracies (data losses or misinterpretations), which is due to the limited coverage of a BIM-based language by implementers [71]. BuildingSMART has previously addressed the issue of the delivery of models between the BIM-authoring and the structural analysis software. In particular, with the release of IFC2×3, the company proposed that the MVD dubbed the 'Structural Analysis View', which covers the exchange requirements (i.e., the information listed above), can be used to transfer the structural analytical model to one or many structural analysis applications. Unfortunately, this MVD often leads to poor quality data exchanges that arise from differences in semantics, syntax, and information representations between the various structural analysis applications [72]. In addition, this MVD was not conceived to address round-tripping exchanges, which are therefore currently impossible to automate as part of the OpenBIM approach.

Commonly, in both cases, a structural information model cannot be used as a comprehensive contribution to a structural analysis. This is because the FEMs produced may be incomplete and require further inputs that are closely linked to the logic of the FEA software and the reference standard utilized. For example, further efforts to finalize the FEMs could involve the load model (i.e., wind, soil and seismic action); the load combinations; the masses; the boundary conditions (springs, rigid links, etc.); and the type of structural analysis employed (modal, linear static, linear dynamic, etc.). However, the issues described here, which strictly depend on the features of the tools being implemented, are just some of the problems that can arise relating to the interoperability between BIM-authoring and FEA software (see [71], for further information).

4.4. BIM Use (2): Production of Shop Drawings

The second BIM use concerns the production of shop drawings of structural elements and systems, and Figure 3 depicts the reference high-level workflow for producing them. This workflow has been adopted in numerous simulations conducted by students (mainly practitioners) undertaking the advanced professional training course—'*BIM: Sustainable Integrated Design*', which has been offered for the past four years by the University of Naples, Federico II. The authors preferred to present contemporary experience with a high-level workflow rather than no workflow at all since no publication in Table 1 provides a reference process map.

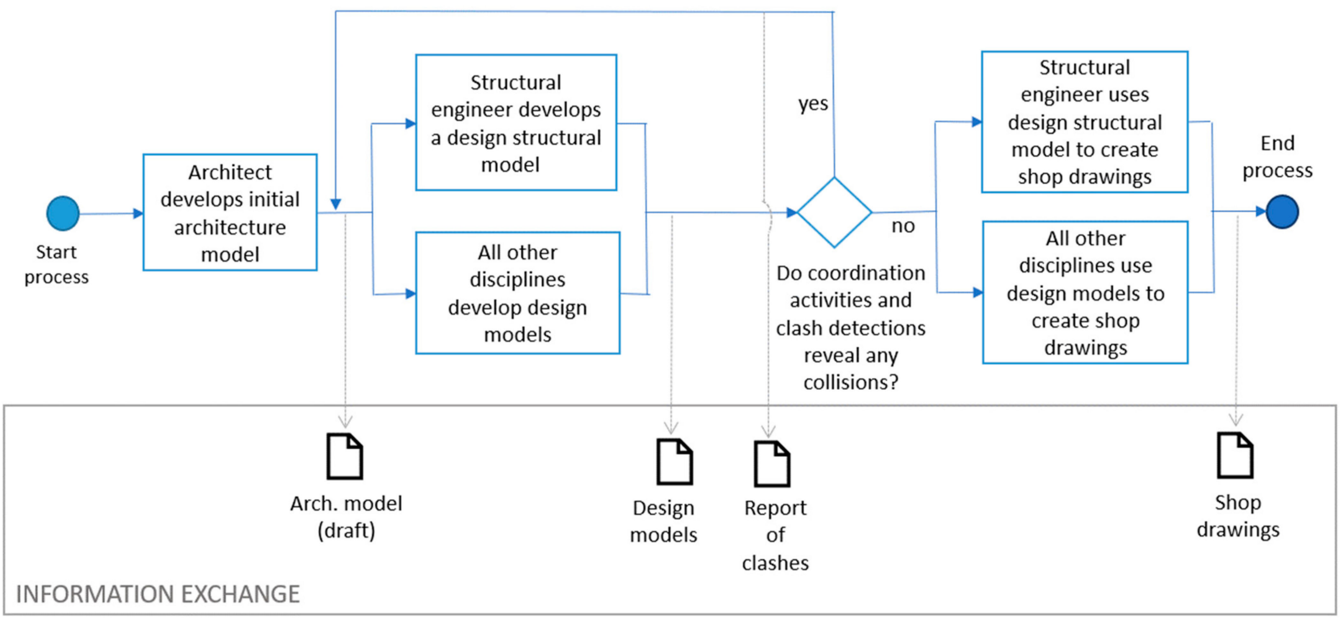

Figure 3. Reference high-level workflow of BIM use (2)—production of shop drawings.

First, an architect develops an initial architecture model, which is used in what follows as a pathway to develop design models of all the other relevant disciplines. The main part of the work involves creating parametric libraries of details, connections, and objects, which ensures that the modelling is efficient and there is geometric compatibility between adjacent pieces [7]. Focusing on the structural discipline, a structural engineer develops the design structural model, which should be produced using the process depicted in Figure 1. The resulting model is composed of 3D objects such as beams, columns, and walls, and contains information about their composition. Successively, there is a decision point where this model is integrated with design models of other disciplines to create federated versions (i.e., where the structural and architectural information models, as well as the MEP and HVAC information models, can be merged). Coordination activities and clash-detections are then performed [36,71] using appropriate applications (interoperability should thus be considered) and collaborative platforms that provide a structured, co-operative environment where information (from different disciplines) can be exchanged and shared. An example of a clash between the structural and the MEP disciplines is depicted in Figure 4. If issues arise, clash-detection activity reports are (automatically) produced at the end of the coordination process; these enable conflicts to be discussed to determine the optimal strategy for resolving them. This generally requires adjustments to be made to design models, which are then further developed by returning to the design stage to ensure integration among disciplines and the production of high-quality deliverables. Coordination activities, clash detections, and use of collaboration platforms are collaborative features of the BIM approach; these are missing in the traditional process for creating shop drawings [17,66].

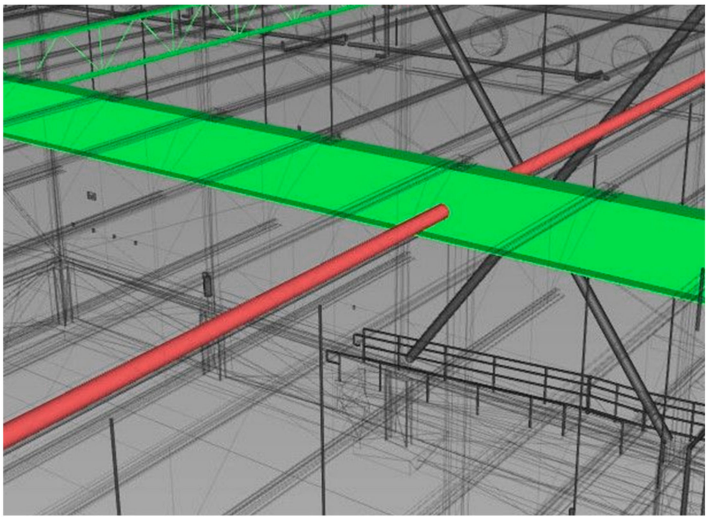

Figure 4. Example of a clash between a structure and the MEP discipline.

If no issues arise, the process progresses, and the structural engineer can use an (integrated) design structural model to easily create views, 3D-views, and shop drawings. This is also the case for other disciplines. The process then ends. If changes are made later, time-consuming reworks are avoided because amendments to the model are also transferred to the shop drawings. This means that these drawings will always reflect the current status of the model [35].

It is worth noting that a traditional workflow, which is based on computer-aided design (CAD), allows the geometry of structural elements and systems to be modelled in a 2D environment; in a BIM-based version, it is possible to create a real-time virtualization of the structural system, with its geometry and details modelled in a 3D environment. In the former, shop drawings are addressed one by one, while the latter defines a unique BIM structural model from which shop drawings and other construction deliverables, such as quantity take-offs and cost estimations, can be derived. The BIM tools and methodologies described thus far are currently, and successfully, used in practice [4].

Limitations

Although the BIM approach addresses the issue of time wasted on reworks, produces high-quality deliverables, and encourages more collaborative perspectives, it also requires considerable software training [7] and a shift to BIM-based workflows [72]. Both of these changes are time-consuming and expensive, but they are both also essential to having a positive effect on productivity challenges. Of course, the activity of modelling a structural information model is only an addition to other established approaches in the structural engineering field. Moreover, reinforcement drawings generated by the model can themselves require significant reworking (see Figure 5) to ensure that they resemble what the participants in the process are used to seeing [35].

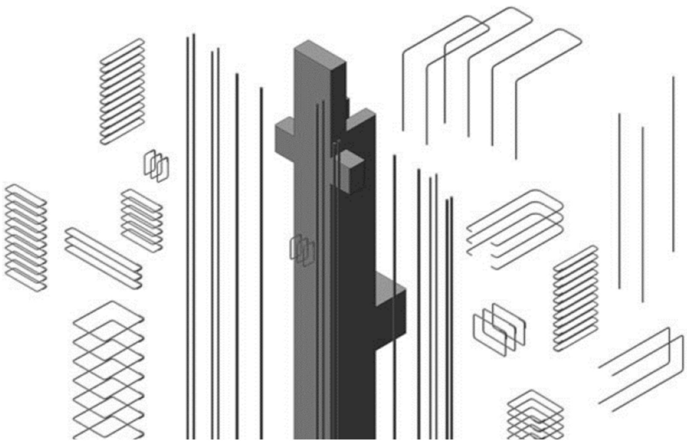

Figure 5. Exploded drawing of a reinforcement model for a column [35].

4.5. BIM Use (3): Optimised Structural Design: Early Identification of Constructability Issues and Comparison of Different Structural Solutions

BIM use (3) focuses on the optimisation of structural design. In fact, BIM tools and methodologies enable both the early identification of some constructability issues and comparisons of different structural design solutions in relation to schedule management, material quantities, and costs.

Usually, constructability issues are addressed in the construction phase [31]. However, structures such as bridges, industrial facilities (e.g., shelters), and tall or unconventional buildings commonly need very industrialized and unique structural elements, meaning that early communication with manufacturers can be crucial from the structural design phase onwards [7,36]. The BIM approach allows the definition of standardized procedures with which to share information (e.g., geometry, sections, and reinforcement of structural members) with manufacturers and receive their feedback during the design process [1]; for example, engineers can deliver a structural information model to manufacturers. They can also visualize and better illustrate the solution proposed, highlight geometrical constraints (curvature, length, etc.) and suggest better design strategies, such as separating structural members into modules to ease and speed up the construction process. This approach is preferable for the types of structure listed above for two main reasons: (1) it avoids the late identification of the constructability issues that can cause major economic losses due to necessary reworks and delays [7]; and (2) as load-bearing structures undergo ongoing development during the construction process, with a consequential effect on structural designs, the intermediate structural assessments required as a result can be produced more easily.

In addition, the BIM approach enables bolder solutions to be considered in the design phase. It also means that a structural information model is available for each solution and can be used to address more purposes at the same time, for example: structural analyses, schedule management, and estimating material quantities and costs. Consequently, it is possible to choose the best solution by comparing construction times, the quantity of the materials that would be used and the costs. In detail, throughout any scheduled simulations, specific BIM tools combine work breakdown structures (WBS) with the objects constituting the structural information model [38]. In this regard, some research has focused on leveraging information models, using automatic open-format BIM technology to extract data [1,39] and identify optimized scheduling solutions. Quantity take-offs relating to structural elements and materials and reinforcements are automatically produced, because the structural information model is composed of parametric objects [41,42]. At the same time, cost estimations are produced by specific BIM tools that link pricing to BIM objects [39,40]. Finally, different structural design solutions can be exchanged with manufacturers to identify constructability issues in advance; thereafter, comparisons are made in terms of construction times, the quantity of the materials used and the costs.

Limitations

The optimization process closely depends on the optimization criteria and methodologies adopted. Indeed, engineers define optimal solutions with respect to established parameters, and so it is both meaningless to speak of absolutely optimal proposals and possibly misleading to define a reference (BIM-based) optimization process. The main limitation arises from defining the optimization procedure to be used, which may require a collaborative approach among stakeholders right from the start.

4.6. BIM Use (4): Seismic Risk Assessments

The fourth BIM use concerns the employment of BIM tools and methodologies to support seismic risk assessments. It should be noted that if the BIM approach is used throughout the lifecycle of a facility, an asset information model (AIM) will be produced after the construction phase. An AIM is composed of several information containers, at the heart of which is a federated BIM model (structural, architectural, MEP, and HVAC). As a result, the BIM model is a unique and centralized source of information on structural and non-structural components (e.g., partitions, wall finishes, and facades), equipment, and systems (e.g., HVAC, electrical, plumbing). Specialist tools used in seismic risk assessments can employ an asset's BIM model to collect more reliable data for use as inputs [44]. This is demonstrated in Figure 6.

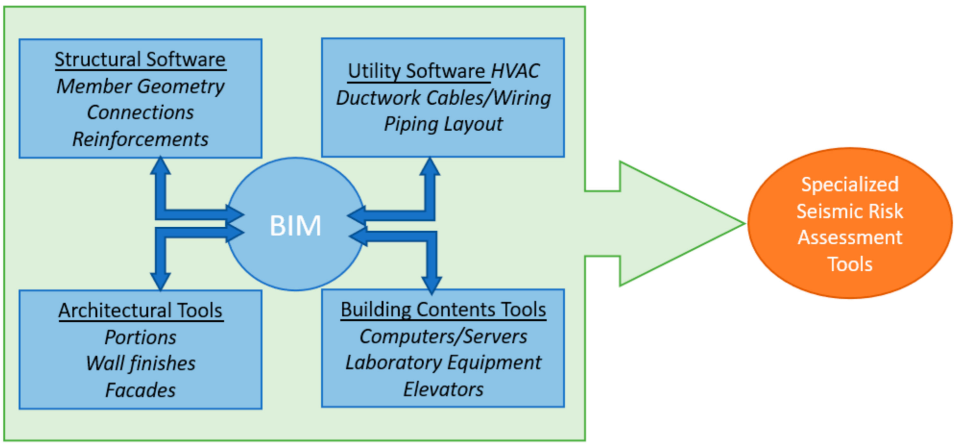

Figure 6. BIM models acting as a store for specialist seismic risk assessment tools [44].

The research on assessing the damage state of buildings, i.e., structural, non-structural, and contents, contains several examples where 3D digital information models are used to provide inputs for the PEER Centre's PBEE methodology [73]. It should be noted that this seismic design approach involves an iterative procedure that starts with the selection of performance objectives (i.e., damage state) and then checks whether they have been met. In this way, information models can be used to produce inputs for structural analysis models [47,50] and fragility parameters (according to FEMA [74]) which can then be added to BIM objects as informative attributes [14,48]. Researchers often develop their own application programming interfaces (APIs) to automatically collect and then import contributions from BIM models into software that performs structural analyses, damage state investigations, and loss assessments (casualties, repair costs or repair times). Some researchers have also investigated the possibility of using BIM models to visualize the results of damage assessments, thereby improving the communication between non-technical stakeholders [43] and providing support for cost-effective seismic mitigation strategies [49], as shown in Figure 7.

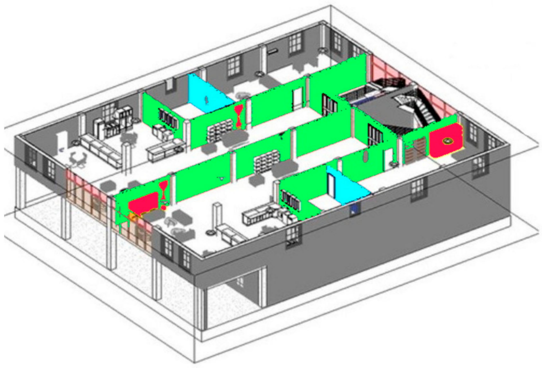

Figure 7. Color-coding of different ranges of seismic risk scores in a 3D digital model [49].

It is worth noting that scholars have also explored the potential of BIM models as input providers, as well as repositories of information for LCAs and LCC [75].

Limitations

The fourth BIM use concerns the employment of multidisciplinary information models to develop reliable data with which to perform seismic risk assessments and visualize the results. Information exchanges (export/import processes) typically involve elaborate automated (or semi-automated) procedures that use APIs developed for this purpose. However, the value of APIs declines in different ways depending on the BIM-authoring software employed to create the 3D digital model and the structural analysis software used for the calculations. The complexity of this calculation currently hinders the definition of a reference workflow, although further research is ongoing, especially in relation to defining simplified calculation procedures [14,48].

4.7. BIM Use (5): Existing Conditions Modelling and Retrofitting of Structures

A number of different structural engineering activities can be required for existing structures: defining their geometrical and mechanical features (e.g., via in-situ inspections, non-destructive and destructive tests, and analyses of available 2D documentation); assessing the ‘as is’ structural performance; and designing structural refurbishment interventions. Consequently, the BIM approach can be used to support (see Table 3):

- Knowledge management.
- The assessment of structural performance.
- The optimization, comparison, and design of structural retrofit strategies.

There are major differences between new and existing structures in relation to the conception of information models. While the process of creating a new building is unique and includes inception and production phases, there is more than one option for existing structures (whether or not a pre-existing information model is available), where the focus shifts to maintenance and deconstruction stages. Figure 8 depicts the two pathways in detail.

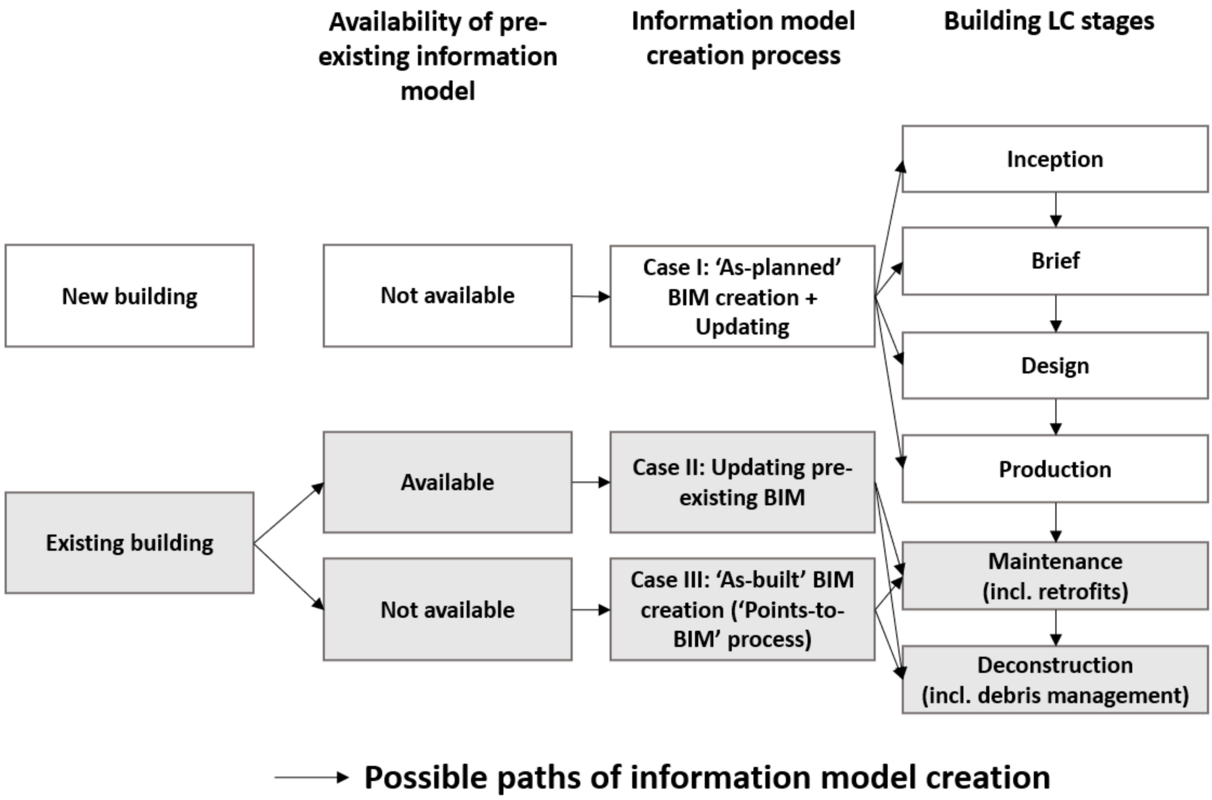

Figure 8. Information model creation processes in new or existing buildings depending on available, pre-existing models and their relationship with lifecycle (LC) stages [25].

Structural engineers analyze the performance of existing buildings and infrastructures when structural retrofit interventions are required. This could be due to a change of destination use, evidence of a poor conservation or damage state, or a lack of compliance with up-to-date building codes. In these circumstances, engineers often have to manage uncertainty about the condition of conservation materials and struggle with a lack of project documentation (e.g., shop drawings, reinforcement details, structural calculation reports). Typically, a pre-existing structural information model is unavailable, and project documentation is therefore essential for defining the geometry of a structural model of an existing building. The documents also provide information on materials, reinforcements and connections, which is essential data for any capacity assessments. A lack of documentation and the absence of pre-existing information models mean that a structural survey is required. Clearly, the capacity assessment is key to this process, which is often conditioned by a lack of information. Indeed, limited knowledge of a structure causes very conservative assumptions to be made about geometries, the mechanical properties of materials, and structural details, leading to underestimates of actual capabilities and overestimates of any retrofit interventions required.

The BIM approach modifies the traditional process used to gather and expand the information needed to define an accurate FEM and perform capacity assessments. Figure 9 shows the reference BIM-based workflow for BIM use (2), relating to assessments of structural performance. The process was developed and validated as part of the 'BIM to CIM' research project conducted by the University of Naples Federico II in collaboration with the Polytechnic of Milan, the Polytechnic of Turin, the IUAV University of Venice, the National Research Centre and Acca Software.

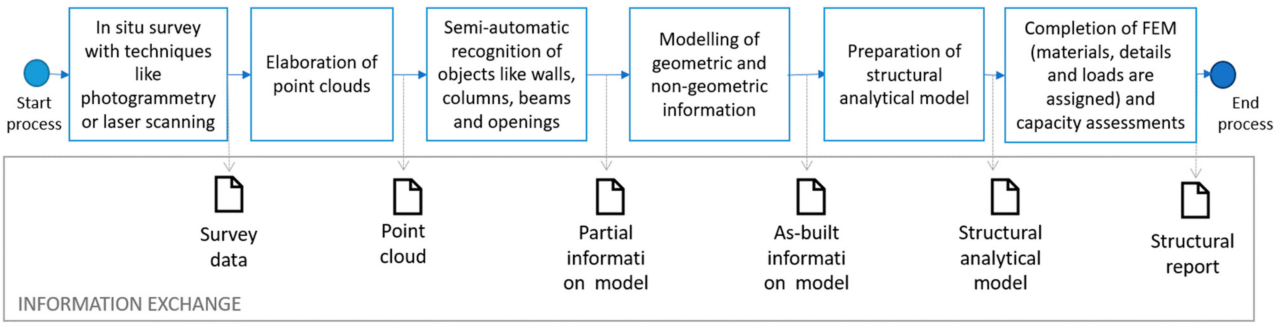

Figure 9. BIM-based workflow for BIM use (5).

The process has six steps: data capture, data processing, object recognition, creation of an as-built information model, preparation of a structural analytical model, completion of a FEM, and a capacity assessment of the structure in the FEA software environment. First, a survey is performed using in-situ techniques such as photogrammetry and 3D laser-scanning [76]. In step two, the data acquired (i.e., images and scans) are expanded in a BIM tool environment to obtain point clouds. In step three, the point cloud is imported into a BIM-authoring environment, thereby enabling the preliminary semi-automatic recognition of BIM objects. Further work is then conducted to produce the as-built information model using the point cloud as a pathway. A structural analytical model is then generated in step five and exported to computational software in order to finalize the FEM. Materials and information on structural details, loads, and constraints are then assigned. Finally, the model is validated through preliminary checks on the distribution of stresses due to gravity loads and the outputs of a modal analysis (periods of vibration and participating masses). In step six, the capacity assessment of the structure is performed, and safety factors are calculated for each structural member. Commonly, these are collected in a structural report. The process then comes to an end.

The great advantages of this workflow are that the geometry in the structural analytical models is more reliable and the FEMs generated are more accurate. Similar workflows are used in the research the authors have identified [52,55,56]. It is worth noting that these workflows are of particular use in historical (mostly masonry) buildings to enable the easy recreation of their details in the form of a digital representation. This use of BIM techniques is generally known as historical BIM (HBIM) [13,77], and examples are available of how it has been applied on a wider scale in historical towns (HT-BIM) [54]. However, there are also examples of applications of BIM techniques to existing bridges [55,56].

Other uncertainties in existing structures, in addition to geometry, relate to the conservation state of the structural materials, which has an obvious impact on the mechanical properties defined in related FEM models. The properties of structural materials are commonly investigated using the in-situ testing of structural elements and the laboratory testing of structural-material samples taken on site. The amount of testing depends on the so-called 'level of knowledge' of a building. In this regard, researchers are exploring the possibility of using information models as repositories for data obtained by testing. This would enable both the level of knowledge to be visualized and the information retrieved to be streamlined for further assessments [57]. Figure 10 contains an example of the visual representation of levels of knowledge.

Finally, a combination of structural information models and collaboration platforms allows project documentation (in-situ and laboratory tests, pre-existing shop drawings, reinforcement details, and structural calculation reports) to be linked to models' objects. In these circumstances, the structural information model becomes a source of reliable, accurate, and easily retrievable data for structural engineers to use during structural refurbishments, retrofits, and maintenance [13].

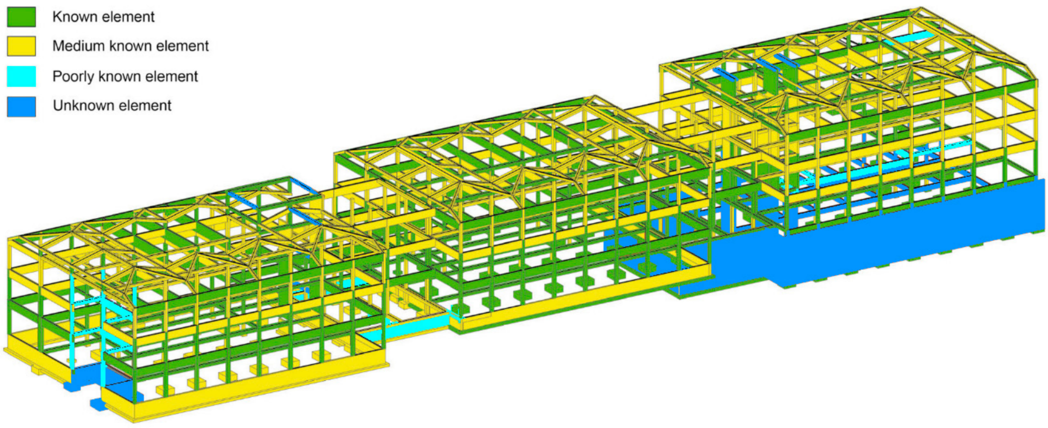

Figure 10. Mapping of the overall level of knowledge of a building [57].

Limitations

The use of BIM tools and methodologies for existing buildings is somewhat recent from a structural engineering perspective. The content analysis of the reference bibliography has highlighted two main trends in how they are applied in these structures. In particular, information models are used to: (1) define more accurate FEMs with models obtained from point clouds produced for information exchanges; and (2) manage structural engineering data from different sources. The first trend is characterized by a different model creation path to that introduced for BIM use (1), which researchers are still validating to prove its benefits. The second trend requires further work on defining clear methodologies for visualizing the data in information models, combining information models and collaboration platforms to manage data from project documentation, and automating the processes used for knowledge acquisition.

4.8. BIM Use (6): Structural Health Monitoring

The sixth BIM use deals with the employment of BIM tools and methodologies to support structural health monitoring. SHM is the process of implementing a damage detection strategy to assess the structural performances of existing buildings and infrastructures. The goal is to detect early stage damage and optimize maintenance strategies using a condition-based approach, thus extending the functional life of a structure [78]. The content analysis of the reference bibliography has identified that SHM uses structural information models as repositories for three main purposes [59]:

- Modelling and visualizing structural performance monitoring systems.
- Managing and visualizing monitoring data.
- Data interpretation and decision-making processes.

Although extremely difficult, Figure 11 contains an example of a reference BIM-based workflow for BIM use (6). This was developed in the Department of Structures for Engineering and Architecture at the University of Naples Federico II, thanks to its employment in several Master's degree projects.

In more detail, structural information models are enriched in the BIM-authoring environment with BIM objects representing the sensor-monitoring system. These models contain a set of informative attributes, for example: name, function, properties, materials, openings, composition, representation and relationship parameters, frequency and temperature set-points, date and time of acquisition, and type of relationship between the sensor and relative building component [13,15]. This as-built structural information model can be exported in the IFC format and uploaded in a cloud-based environment which, in the BIM approach, is essentially a collaboration platform. This environment enables SHM-related data to be integrated into structural information models, although issues arise concerning exchanges of this information and the visualization of the monitoring process. In this regard, researchers have proposed extending the IFC schema using either a custom property set to retain informative attributes [58,60], or a real-life IFC-schema extension known as an IFC monitor [63]. Furthermore, in 2018, Davila Delgado et al. [58] highlighted that there are no formal directives for managing and visualizing sensor data in a BIM environment. As a result, his team developed a dynamic BIM viewer, which is a user-friendly tool that allows the key parameters of a built asset's structural performance to be communicated in a dynamic and interactive manner. Tools of this kind may enable the interpretation and analysis of data, making them a valuable and reliable way to obtain information for use in decision-making processes concerning refurbishment and maintenance interventions.

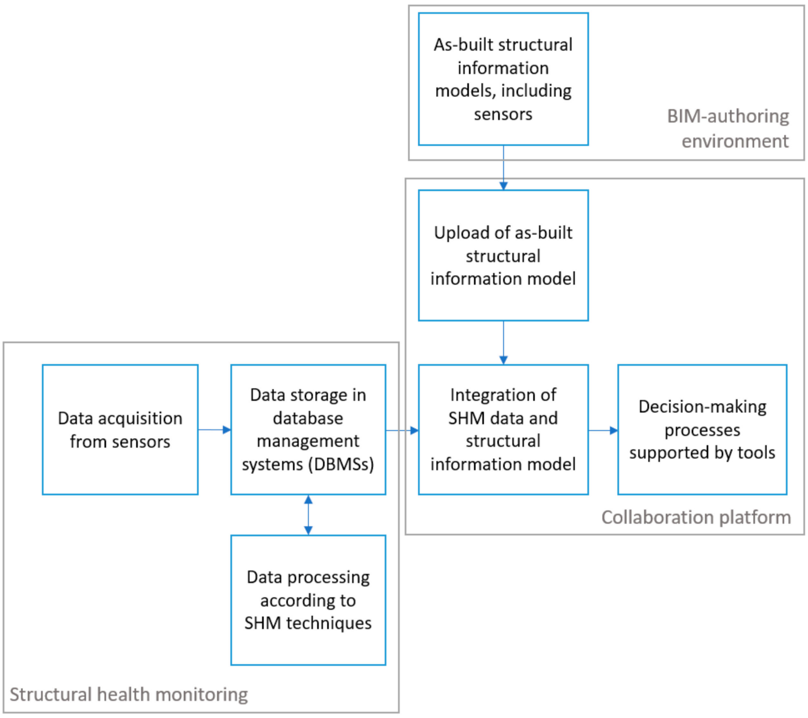

Figure 11. Example of reference framework for BIM use (6).

Limitations

Unfortunately, BIM tools and methodologies have only recently been used in relation to the sixth BIM use, meaning that researchers are still focusing on ideal case studies. Further work is therefore required to resolve many interoperability issues, as well as problems with the post-processing and visualization of data. Accordingly, validated reference workflows still need to be defined.

5. Discussion

Research on the use of BIM in structural engineering has increased in the last decade; however, no real state-of-the-art or account of contemporary experience is available on the subject. The 2019 bibliometric literature review by Vilutiene et al. [16] does examine (automatically) a very large number of publications (over 300), identifying variations in the main topics and keywords over the last decade and adopting clusters to present in-depth analyses of the data obtained. According to the authors, however, these interesting results do not provide a state-of-the-art or an account on contemporary experience on BIM applications in structural engineering, because there is no presentation of detected methodologies and applications which the authors regard as essential. The authors' manual approach was fundamental to enable them to analyze possibly relevant publications in order to highlight content that refers to structural engineering specifically. In fact, a preliminary analysis of the examined papers in Vilutiene et al. [16] reveals substantial contamination from fields such as construction engineering and architecture, explaining the significant difference between their methodology and the authors' traditional literature review, which considered just 45 papers in great detail. Moreover, the authors' focus is not on the technical features of software tools for use in information modelling and structural analyses for specific reasons: (1) how quickly these tools now change and the high number of applications available, which makes it difficult to produce an exhaustive list; and (2) in an attempt to prevent readers being conditioned with specified opportunities and limitations as, instead, the authors preferred to illustrate workflows and discuss information exchanges to highlight innovations for structural engineering arising from the BIM approach.

In detail, the authors' methodology comprised a traditional literature review and a qualitative in-depth analysis of the publications identified. This has enabled them to distinguish six main areas of research and the corresponding BIM uses in terms of their workflows, information exchanges, employment of information models, and limitations. According to the authors, therefore, this paper contains an extensive account of the contemporary experience. Nevertheless, the authors also consider gaps in knowledge, likely developments, and the repercussions of this research more broadly.

BIM uses (1) and 2, which are typical of the design phase, are currently employed by practitioners and represent the authors' initial research on the involvement of BIM in structural engineering processes (see the results of the literature review in Table 1). In relation to BIM use (1), interoperability issues between BIM-authoring software and BIM tools for structural calculations have attracted the attention of researchers in the past but are no longer a major research issue. Indeed, the focus of studies today is on the development of new work procedures to improve the effectiveness and efficiency of current design processes.

This is also the case for *BIM use (3)*, which focuses on leveraging BIM tools and methodologies to optimize early-stage structural design processes consistent with specific economic and construction criteria. Generally, this optimization involves elaborate procedures that require a capacity to develop more than one solution at the same time to identify which is the best. In reality, there is no single optimum solution in structural design, but there may be one that is the best in certain circumstances, consistent with established criteria. The issue of optimization struggles for inclusion in projects using traditional tools, because it is a time-consuming procedure and depends on the availability of information that is required in advance. The focus of most researchers is still on defining and standardizing BIM-based processes to improve structural designs. Nevertheless, the authors have not included a specific workflow for BIM use (3) in this paper, because of the high number of optimization approaches available and the subjectivity of the criteria adopted. Over the next few years, further developments could, however, be fostered by the new and emerging technology of artificial intelligence (AI) [79,80]. Indeed, a recent trend involves using integrated BIM and AI technologies to enable generative designs that aim to resolve complex optimization problems that may arise in the structural design stage [81].

In *BIM use (4)*, the authors highlight the potential of the BIM approach to increase the use of more sophisticated design methodologies on the ground, especially for seismic risk assessments (e.g., PBEE, damage analyses). These consider non-structural (and, therefore, multidisciplinary) elements in the structural design phase, and thus struggle to be adopted in (traditional) current practice, because these analyses can be complex, expensive, and time-consuming. Research is focusing on developing simplified procedures for seismic risk assessments that can exploit information models to extract inputs for analyses and present results effectively. Such methodologies would be particularly valuable in countries such as Italy, where there are territories with high seismic activity, and where both public and private clients may start to demand better structural performances than those guaranteed by the current building code. Further research is, however, required to define a (or an expanded) reference BIM-based workflow.

In *BIM use (5)*, the authors demonstrate that the BIM approach can be used in existing structures in relation to the assessment of structural performance, the (optimised) design of structural retrofits, and knowledge management. Intentionally, the authors have first underlined a substantial difference between this case and the use of BIM in new structures, as well as the absence of the information models produced in the preliminary design phase for new buildings and, therefore, the requirement to create models starting with surveys of real assets and studies of corresponding 2D documentation, which may be unreliable or unavailable for both the design and construction phases (e.g., a requirement to deposit documentation with building regulatory authorities was only enforced in Italy in 1971). Nevertheless, the authors provide a workflow that applies to undamaged existing structures, which is a common scenario, but existing structures that have sustained damage must also be considered in the future. In 2019, Musella et al. [82] have conducted preliminary research on using a combination of BIM and AI to assess seismic damage in post-earthquake scenarios through image processing. However, further work is necessary in this regard, as well as with respect to the development of frameworks that combine collaboration platforms and information models to create central databases for organizing, retrieving, and managing data relating to in-situ tests and inspections.

Finally, *BIM use (6)*, which refers to the operation and maintenance phase of structures, is extremely sectoral, but can, at the same time, also represent a stand-alone design objective. As seen in the analysis in Table 2, the applications of the BIM approach to SHM mainly concern bridges, which are infrastructures where the structural engineering discipline is dominant. The interest of the scientific community in the combined use of BIM and SHM is very recent, which is particularly demonstrated by the high number of conference proceedings among the publications identified. However, the topic is more complex than the other BIM uses, requiring the evaluation of strategies for integrating tools to conduct monitoring (briefly referred to as the internet of things (IoT)), update information models, and provide input data for SHM.

Relationship between Model and Process in the BIM Approach

Unfortunately, the BIM acronym is often, and improperly, thought to be synonymous with BIM-authoring software, leading to a misleading notion that it is more performance software than CAD. In reality, there is a relationship between model and process in the BIM approach, with each being essential to the other. According to the authors, having good knowledge of the technology and tools used to create information models is unproductive if the information stored is not the result of informative processes that ensure its consistency and integrity. Information is crucial in the BIM approach, and so its quality is the key factor in whether a project will, or will not, be successful. In other words, BIM tools and methodologies are a way to safeguard the quality of the information provided by the AEC industry throughout the lifecycle of a facility and in relation to all of the disciplines involved in a project. The resulting information models and related information containers contribute to the definition of both a project information model, from the concept stage to the handover and close-out phases, and to an AIM in the operation and management stage. The authors' conclusions are set out in Section 6 below.

6. Conclusions

This paper provides the first account of the contemporary experience on the use of BIM in structural engineering. According to the authors, research on the use of BIM in structural engineering has a prominent role to play in mitigating shortcomings that originate from the typical cultural background of structural engineers; they often lack, indeed, an aptitude for process identification, multidisciplinary collaboration, and information management. In this regard, it is worth noting that while the BIM approach has no own agenda for only research purposes, it is the focus of applied research with the purpose of aiding professional practice. In fact, there are fundamental differences between the BIM and traditional approaches, with the former enabling the development of standardized information processes and the management of information flows. Consequently, the research proposed in this paper can be a valuable reference starting point for both practitioners and researchers who are interested in the adoption of BIM in structural engineering. However, the case of new buildings is the most mature and is where structural engineers can currently best apply the

BIM approach and tools. The case of BIM for existing buildings deserves further attention from a structural engineering point of view because appropriate BIM-based methodologies are needed to replace traditional work processes and reducing their deficiencies.

In conclusion, in the next future, it is expected that the integration between BIM and the IoT will enable the digital twin era in the AEC industry [83], i.e., information models become digital twins of real as-built assets, with their performance (e.g., temperature, energy consumption, structural functioning) monitored and updated in real-time. Research on the use of BIM in structural engineering would be fundamental to aid practitioners in adopting this framework where AI algorithms could be used to highlight possible issues and provide forecasts in relation to various maintenance scenarios [84,85]. Additionally, digital twins could also be adapted to both new and existing buildings. Finally, additional developments are also expected in openBIM-based research in structural engineering that will focus mainly on the strategic infrastructures (such as bridges), with particular attention paid to the monitoring and maintenance phases. As an example, to overcome the limitations of the previous scheme, which was conceived for buildings [86], the buildingSMART community released IFC version 4.2 in 2019, which was conceived from the IFC bridge extension project.

Author Contributions: Investigation, V.C.; Methodology, D.A.; Supervision, E.C. and G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*; John Wiley & Sons: Hoboken, NJ, USA, 2011; ISBN 0470541377.
2. Grilo, A.; Jardim-Goncalves, R. Value proposition on interoperability of BIM and collaborative working environments. *Autom. Constr.* **2010**, *19*, 522–530. [CrossRef]
3. Azhar, S. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadersh. Manag. Eng.* **2011**, *11*, 241–252. [CrossRef]
4. Edirisinghe, R.; London, K. Comparative Analysis of International and National Level BIM Standardization Efforts and BIM adoption. In Proceedings of the 32nd CIB W78 Conference 2015, Eindhoven, The Netherlands, 27–29 October 2015; pp. 149–158.
5. European Union. Directive 2014/23/EU of the European Parliament and of the Council of 26 February 2014 on the award of concession contracts. *Off. J. Eur. Union* **2014**, *L 94/1*, 1–64.
6. Muñoz-La Rivera, F.; Vielma, J.C.; Herrera, R.F.; Carvallo, J. Methodology for Building Information Modeling (BIM) Implementation in Structural Engineering Companies (SECs). *Adv. Civ. Eng.* **2019**, *2019*, 1–16. [CrossRef]
7. Kaner, I.; Sacks, R.; Kassian, W.; Quitt, T. Case studies of BIM adoption for precast concrete design by mid-sized structural engineering firms. *J. Inf. Technol. Constr.* **2008**, *13*, 303–323.
8. Schinler, D.; Nelson, E. BIM and the structural engineering community. *Structure* **2008**, *12*, 10–12.
9. Fedorik, F.; Makkonen, T.; Heikkilä, R. Integration of BIM and FEA in automation of building and bridge engineering design. In Proceedings of the ISARC International Symposium on Automation and Robotics in Construction, Auburn, AL, USA, 18–21 July 2016; Volume 33, pp. 1–6.
10. Pukl, R.; Pálek, P.; Červenka, J. The possibility of using BIM for nonlinear life-cycle analysis of concrete structures. In Proceedings of the Fifth International Symposium on Life-Cycle Civil Engineering (IALCCE 2016), Delft, The Netherlands, 16–20 October 2016; pp. 655–661.
11. Ren, R.; Zhang, J.; Dib, H.N. BIM Interoperability for Structure Analysis. In Proceedings of the Construction Research Congress 2018, New Orleans, LA, USA, 2–4 April 2018; pp. 470–479.
12. Hasan, A.M.M.; Torky, A.A.; Rashed, Y.F. Geometrically accurate structural analysis models in BIM-centered software. *Autom. Constr.* **2019**, *104*, 299–321. [CrossRef]
13. Bruno, S.; De Fino, M.; Fatiguso, F. Historic Building Information Modelling: Performance assessment for diagnosis-aided information modelling and management. *Autom. Constr.* **2018**, *86*, 256–276. [CrossRef]
14. Vitiello, U.; Ciotta, V.; Salzano, A.; Asprone, D.; Manfredi, G.; Cosenza, E. BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings. *Autom. Constr.* **2019**, *98*, 90–101. [CrossRef]

15. Banfi, F.; Barazzetti, L.; Previtali, M.; Roncoroni, F. Historic Bim: A New Repository for Structural Health Monitoring. *ISPRS-Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-5/W1*, 269–274. [CrossRef]
16. Vilutiene, T.; Kalibatiene, D.; Hosseini, M.R.; Pellicer, E.; Zavadskas, E.K. Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature. *Adv. Civ. Eng.* **2019**, *2019*, 1–19. [CrossRef]
17. Sacks, R.; Treckmann, M.; Rozenfeld, O. Visualization of Work Flow to Support Lean Construction. *J. Constr. Eng. Manag.* **2009**, *135*, 1307–1315. [CrossRef]
18. ISO 19650-1: 2018-Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 1: Concepts and Principles. 2018. Available online: https://www.iso.org/standard/68078.html (accessed on 2 January 2021).
19. ISO 19650-2: 2018 Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling. Part 2: Delivery Phae of the Aset. 2018. Available online: https://www.iso.org/standard/68080.html (accessed on 2 January 2021).
20. Interoperability: The Ability of Computer Systems or Software to Exchange and Make Use of Information. Available online: https://www.ice.org.uk/getattachment/news-and-insight/the-civil-engineer/june/overcome-interoperability-challenge/Interoperability-Information-Sheet-(1).pdf.aspx (accessed on 26 April 2021).
21. openBIM-buildingSMART International. Available online: https://www.buildingsmart.org/about/openbim (accessed on 26 April 2021).
22. ISO 29481-1:2016-Building Information Models—Information Delivery Manual—Part 1: Methodology and Format. 2018. Available online: https://www.iso.org/standard/60553.html (accessed on 12 March 2021).
23. ISO 16739-1:2018-Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries-Part 1: Data Shema. 2018. Available online: https://www.iso.org/standard/70303.html (accessed on 4 January 2021).
24. ISO 29481-2:2012-Building Information Models–Information Delivery Manual–Part 2: Interaction Framework. 2012. Available online: https://www.iso.org/standard/55691.html (accessed on 12 March 2021).
25. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings-Literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
26. MVD Database-buildingSMART Technical. Available online: https://technical.buildingsmart.org/standards/ifc/mvd/mvd-database/ (accessed on 26 April 2021).
27. Olawumi, T.O.; Chan, D.W.M.; Wong, J.K.W. Evolution in the intellectual structure of bim research: A bibliometric analysis. *J. Civ. Eng. Manag.* **2017**, *23*, 1060–1081. [CrossRef]
28. Santos, R.; Costa, A.A.; Grilo, A. Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Autom. Constr.* **2017**, *80*, 118–136. [CrossRef]
29. Lee, S.-I.; Bae, J.-S.; Cho, Y.S. Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures. *Autom. Constr.* **2012**, *23*, 20–32. [CrossRef]
30. Bhusar, A.A.; Akhare, A.R. Application of BIM in structural engineering. *Int. J. Civ. Eng.* **2014**, *1*, 12–20.
31. Chi, H.-L.; Wang, X.; Jiao, Y. BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes. *Arch. Comput. Methods Eng.* **2015**, *22*, 135–151. [CrossRef]
32. Liu, Z.-Q.; Zhang, F.; Zhang, J. The building information modeling and its use for data transformation in the structural design stage. *J. Appl. Sci. Eng.* **2016**, *19*, 273–284. [CrossRef]
33. Shin, T.S. Building information modeling (BIM) collaboration from the structural engineering perspective. *Int. J. Steel Struct.* **2017**, *17*, 205–214. [CrossRef]
34. Baran, W.; Żymańczyk, B. Structural Engineering by way of BIM. *MATEC Web Conf.* **2018**, *174*, 04011. [CrossRef]
35. Fink, T. BIM for Structural Engineering. In *Building Information Modeling*; Borrmann, A., König, M., Koch, C., Beetz, J., Eds.; Springer: Cham, Switzerland, 2018; pp. 329–336. ISBN 9783319928623.
36. Jeong, Y.-S.; Eastman, C.M.; Sacks, R.; Kaner, I. Benchmark tests for BIM data exchanges of precast concrete. *Autom. Constr.* **2009**, *18*, 469–484. [CrossRef]
37. Hu, Z.; Zhang, J. BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials. *Autom. Constr.* **2011**, *20*, 167–180. [CrossRef]
38. Zhang, J.P.; Hu, Z.Z. BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Autom. Constr.* **2011**, *20*, 155–166. [CrossRef]
39. Faghihi, V.; Reinschmidt, K.F.; Kang, J.H. Objective-driven and Pareto Front analysis: Optimizing time, cost, and job-site movements. *Autom. Constr.* **2016**, *69*, 79–88. [CrossRef]
40. Cheung, F.K.T.; Rihan, J.; Tah, J.; Duce, D.; Kurul, E. Early stage multi-level cost estimation for schematic BIM models. *Autom. Constr.* **2012**, *27*, 67–77. [CrossRef]
41. Monteiro, A.; Poças Martins, J. A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Autom. Constr.* **2013**, *35*, 238–253. [CrossRef]
42. Choi, J.; Kim, H.; Kim, I. Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage. *J. Comput. Des. Eng.* **2015**, *2*, 16–25. [CrossRef]

43. Christodoulou, S.E.; Vamvatsikos, D.; Georgiou, C. A BIM-based framework for forecasting and visualizing seismic damage, cost and time to repair. In Proceedings of the 8th European Conference on Product and Process Modelling (ECCPM), Cork, Ireland, 14–16 September 2010.
44. Welch, D.P.; Sullivan, T.J.; Filiatrault, A. Potential of Building Information Modelling for seismic risk mitigation in buildings. *Bull. N. Z. Soc. Earthq. Eng.* **2014**, *47*, 253–263. [CrossRef]
45. Perrone, D.; Filiatrault, A. Automated seismic design of non-structural elements with building information modelling. *Autom. Constr.* **2017**, *84*, 166–175. [CrossRef]
46. Anil, E.B.; Akinci, B.; Kurc, O.; Garrett, J.H. Building-Information-Modeling–Based Earthquake Damage Assessment for Reinforced Concrete Walls. *J. Comput. Civ. Eng.* **2016**, *30*, 04015076. [CrossRef]
47. Alirezaei, M.; Noori, M.; Tatari, O.; Mackie, K.R.; Elgamal, A. BIM-based Damage Estimation of Buildings under Earthquake Loading Condition. *Procedia Eng.* **2016**, *145*, 1051–1058. [CrossRef]
48. Xu, Z.; Lu, X.; Zeng, X.; Xu, Y.; Li, Y. Seismic loss assessment for buildings with various-LOD BIM data. *Adv. Eng. Inform.* **2019**, *39*, 112–126. [CrossRef]
49. Valinejadshoubi, M.; Bagchi, A.; Moselhi, O. Identifying At-Risk Non-Structural Elements in Buildings Using BIM: A Case Study Application. *J. Earthq. Eng.* **2020**, *24*, 869–880. [CrossRef]
50. Zou, D.; Chen, K.; Kong, X.; Yu, X. An approach integrating BIM, octree and FEM-SBFEM for highly efficient modeling and seismic damage analysis of building structures. *Eng. Anal. Bound. Elem.* **2019**, *104*, 332–346. [CrossRef]
51. Ilter, D.; Ergen, E. BIM for building refurbishment and maintenance: Current status and research directions. *Struct. Surv.* **2015**, *33*, 228–256. [CrossRef]
52. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Oreni, D.; Previtali, M.; Roncoroni, F.; Schiantarelli, G. BIM from laser clouds and finite element analysis: Combining structural analysis and geometric complexity. *ISPRS-Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *XL-5/W4*, 345–350. [CrossRef]
53. Bassier, M.; Hadjidemetriou, G.; Vergauwen, M.; Van Roy, N.; Verstrynge, E. Implementation of Scan-to-BIM and FEM for the Documentation and Analysis of Heritage Timber Roof Structures. In *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*; Springer: Cham, Switzerland, 2016; Volume 10058. [CrossRef]
54. Pelliccio, A.; Saccucci, M.; Grande, E. HT_BIM: Parametric modelling for the assessment of risk in historic centers. *Disegnarecon* **2017**, *10*, 1–5.
55. Hüthwohl, P.; Brilakis, I.; Borrmann, A.; Sacks, R. Integrating RC Bridge Defect Information into BIM Models. *J. Comput. Civ. Eng.* **2018**, *32*, 04018013. [CrossRef]
56. Shim, C.S.; Kang, H.R.; Dang, N.S.; Lee, D.K. Development of BIM-based bridge maintenance system for cable-stayed bridges. *Smart Struct. Syst.* **2017**, *20*, 697–708.
57. Ugliotti, F.M.; Osello, A.; Rizzo, C.; Muratore, L. BIM-based structural survey design. *Procedia Struct. Integr.* **2019**, *18*, 809–815. [CrossRef]
58. Dávila, D.J.M.; Brilakis, I.; Middleton, C. Open data model standards for structural performance monitoring of infrastructure assets. In Proceedings of the 32nd CIB W78 Conference, Eindhoven, The Netherlands, 27–29 October 2015; Elsevier: Amsterdam, The Netherlands, 2015.
59. Davila Delgado, J.M.; Butler, L.J.; Gibbons, N.; Brilakis, I.; Elshafie, M.Z.E.B.; Middleton, C. Management of structural monitoring data of bridges using BIM. *Proc. Inst. Civ. Eng.-Bridg. Eng.* **2017**, *170*, 204–218. [CrossRef]
60. Theiler, M.; Dragos, K.; Smarsly, K. BIM-based design of structural health monitoring systems. In Proceedings of the 11th International Workshop on Structural Health Monitoring, Stanford, CA, USA, 12–14 September 2017.
61. Davila Delgado, J.M.; Butler, L.J.; Brilakis, I.; Elshafie, M.Z.E.B.; Middleton, C.R. Structural Performance Monitoring Using a Dynamic Data-Driven BIM Environment. *J. Comput. Civ. Eng.* **2018**, *32*, 04018009. [CrossRef]
62. Valinejadshoubi, M.; Bagchi, A.; Moselhi, O.; Shakibabarough, A. Investigation on the potential of building information modeling in structural health monitoring of buildings. *CSCE Gen. Conf.* **2018**, *2018*, 407–416.
63. Theiler, M.; Smarsly, K. IFC Monitor–An IFC schema extension for modeling structural health monitoring systems. *Adv. Eng. Inform.* **2018**, *37*, 54–65. [CrossRef]
64. Messner, J.; Anumba, C.; Dubler, C.; Goodman, S.; Kasprzak, C.; Kreider, R.; Leicht, R.; Saluja, C.; Zikic, N. *BIM Project Execution Planning Guide*; Version 2.2; Computer Integrated Construction Research Program; The Pennsylvania State University: State College, PA, USA, 2019.
65. BIMe INITIATIVE 211in Model Uses Table. Available online: https://bimexcellence.org/wp-content/uploads/211in-Model-Uses-Table.pdf (accessed on 26 April 2021).
66. Sacks, R.; Barak, R. Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice. *Autom. Constr.* **2008**, *17*, 439–449. [CrossRef]
67. Tsay, R.-J. A Study of BIM Combined with ETABS in Reinforced Concrete Structure Analysis. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *233*, 22024. [CrossRef]
68. Aldegeily, M.; Zhang, J.; Hu, Y.; Shao, X. From Architectural Design to Structural Analysis: A Data-Driven Approach to Study Building Information Modeling (BIM) Interoperability. Ph.D. Thesis, Western Michigan University, Kalamazoo, MI, USA, 2018. Available online: http://ascpro0.ascweb.org/archives/cd/2018/paper/CPRT152002018.pdf (accessed on 16 February 2021).

69. Hu, Z.Z.; Zhang, X.Y.; Wang, H.W.; Kassem, M. Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Autom. Constr.* **2016**, *66*, 29–42. [CrossRef]
70. Tchouanguem Djuedja, J.F.; Karray, M.H.; Foguem, B.K.; Magniont, C.; Abanda, F.H. Interoperability Challenges in Building Information Modelling (BIM) BT-Enterprise Interoperability VIII. In *Enterprise Interoperability VIII*; Popplewell, K., Thoben, K.-D., Knothe, T., Poler, R., Eds.; Springer: Cham, Switzerland, 2019; pp. 275–282.
71. Lu, N.; Korman, T. Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and Challenges. In Proceedings of the Construction Research Congress 2010, Banff, AB, Canada, 8–10 May 2010; American Society of Civil Engineers: Reston, VA, USA, 2010; pp. 1136–1145.
72. Matthews, J.; Love, P.E.D.; Heinemann, S.; Chandler, R.; Rumsey, C.; Olatunj, O. Real time progress management: Re-engineering processes for cloud-based BIM in construction. *Autom. Constr.* **2015**, *58*, 38–47. [CrossRef]
73. Günay, M.S.; Mosalam, K.M. PEER Performance Based Earthquake Engineering Methodology, Revisited. *J. Earthq. Eng.* **2003**, *17*, 829–858. [CrossRef]
74. Hamburger, R.O.; Rojahn, C.; Heintz, J.; Mahoney, M.G. FEMA P58: Next-generation building seismic performance assessment methodology. In Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24–28 September 2012; Volume 10.
75. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Integration of LCA and LCC analysis within a BIM-based environment. *Autom. Constr.* **2019**, *103*, 127–149. [CrossRef]
76. Arayici, Y. Towards building information modelling for existing structures. *Struct. Surv.* **2008**, *26*, 210–222. [CrossRef]
77. Murphy, M.; McGovern, E.; Pavia, S. Historic building information modelling (HBIM). *Struct. Surv.* **2009**, *27*, 311–327. [CrossRef]
78. Farrar, C.R.; Worden, K. An introduction to structural health monitoring. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2007**, *365*, 303–315. [CrossRef] [PubMed]
79. Tang, S.; Shelden, D.R.; Eastman, C.M.; Pishdad-Bozorgi, P.; Gao, X. A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Autom. Constr.* **2019**, *101*, 127–139. [CrossRef]
80. Shahinmoghadam, M.; Motamedi, A. Review of BIM-centred IoT Deployment–State of the Art, Opportunities, and Challenges. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC 2019), Banff, AB, Canada, 21–24 May 2019; pp. 1268–1275.
81. Tafraout, S.; Bourahla, N.; Bourahla, Y.; Mebarki, A. Automatic structural design of RC wall-slab buildings using a genetic algorithm with application in BIM environment. *Autom. Constr.* **2019**, *106*, 102901. [CrossRef]
82. Musella, C.; Serra, M.; Menna, C.; Asprone, D. BIM & AI: Advanced technologies for the digitalisation of seismic damages in masonry buildings. In Proceedings of the International fib Symposium on Conceptual Design of Structures, Madrid, Spain, 26–28 September 2019.
83. Lamb, K. *Principle-Based Digital Twins: A Scoping Review*; CDBB, University of Cambridge: Cambridge, UK, 2019. [CrossRef]
84. Cheng, J.C.P.; Chen, W.; Chen, K.; Wang, Q. Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Autom. Constr.* **2020**, *112*, 103087. [CrossRef]
85. Li, J.; Kassem, M.; Ciribini, A.L.C.; Bolpagni, M. A Proposed Approach Integrating DLT, BIM, IoT and Smart Contracts: Demonstration Using a Simulated Installation Task. In Proceedings of the International Conference on Smart Infrastructure and Construction 2019 (ICSIC), Cambridge, UK, 8–10 July 2019; pp. 275–282.
86. Borrmann, A.; Muhic, S.; Hyvärinen, J.; Chipman, T.; Jaud, S.; Castaing, C.; Dumoulin, C.; Liebich, T.; Mol, L. The IFC-Bridge project–Extending the IFC standard to enable high-quality exchange of bridge information models. In Proceedings of the 2019 European Conference on Computing in Construction Chania, Crete, Greece, 10–12 July 2019; pp. 377–386.