Building Information Modeling (BIM) for existing buildings – literature review and future needs

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Abstract

While BIM processes are established for new buildings, the majority of existing buildings is not maintained, refurbished or deconstructed with BIM yet. Promising benefits of efficient resource management motivate research to overcome uncertainties of building condition and deficient documentation prevalent in existing buildings.

Due to rapid developments in BIM research, involved stakeholders demand a state-of-the-art overview of BIM implementation and research in existing buildings. This paper presents a review of over recent 180 publications on the topic. Results show scare BIM implementation in existing buildings yet, due to challenges of (1) high modeling/conversion effort from captured building data into semantic BIM objects, (2) updating of information in BIM and (3) handling of uncertain data, objects and relations in BIM occurring in existing buildings.

Despite fast developments and spreading standards, challenging research opportunities arise from process automation and BIM adaption to existing buildings' requirements.

Keywords –As-built BIM (Building Information Modeling)[2], Existing buildings, Facility management (FM)[1], Maintenance[1], Retrofits[1], Deconstruction[1], Dismantling[1], Demolition[1], , 'Scan-to-BIM', Reverse engineering

Paper type - Review paper

1 Introduction

Resource scarcity, sustainability challenges and stricter decrees for recycling and resource efficiency in buildings [1] motivate the Architecture, Engineering, Construction, Facility Management (FM) and Deconstruction[1] communities to manage resources efficiently [2]. Due to long building life cycles, maintenance and deconstruction management are likewise major levers to cope with resource efficiency and to enable closed-loop material cycles. Especially in industrialized countries with low new construction rates, activities of the construction sector increasingly shift to building modifications, retrofits and deconstruction of existing buildings [3,4].

In the past decades, there had been a growing interest of the construction sector in using Building Information Models (BIM)[2] due to many benefits and resource savings during design, planning, and construction of new buildings [5–9]. Development of 3D modeling started in the 1970s, based on the

[1] In this paper we use the term 'deconstruction' for the denomination of the last building LC stage with further subcategories. Other sources like ISO 22263:2008 or OmniClass Table 32:2012 refer to this stage synonymously as 'demolition', 'decommissioning', 'disassembling', 'dismantling', 'recycling' or 'end-of-life'. Besides, we use the term 'maintenance' for the LC stage of building service life with synonyms like 'operations and maintenance', 'facility management', 'retrofit' or 'refurbishment'.

[2] Synonyms: Building Construction Information Model, Building Information Modeling

early computer-aided design (CAD) efforts in several industries. While many industries developed integrated analysis tools and object-based parametric modeling (being the basic concept of BIM), the construction sector confined for quite some time to the traditional 2D design [7,8]. BIM modeling was introduced in pilot projects in the early 2000s [3] to support building design of architects and engineers. Consequently, major research trends focused on the improvement of preplanning and design, clash detection, visualization, quantification, costing and data management [7,10]. Lately, specialized tools of design, architecture and engineering professions join the basic functionalities, such as energy analysis, structural analysis, scheduling, progress tracking or jobsite safety [11]. The use of BIM concentrates on preplanning, design, construction and integrated project delivery of buildings and infrastructure, but since recently, research focus shifts from earlier life cycle (LC) stages to maintenance, refurbishment, deconstruction and end-of-life considerations [2,7,11–15] especially of complex structures.

Buildings and structures differ in types of use (e.g. residential, commercial, municipal, infrastructural), in age (e.g. new[3], existing[4], heritage) and in ownership (e.g. private owner, housing association, authorities, universities). These differing framework conditions are influencing the application of BIM, its level of detail (LoD) and its supporting functionalities regarding design, construction, maintenance and deconstruction processes due to stakeholders' requirements.

According to recent surveys, BIM is suitable for larger and more complex buildings and applied by the respondents of recent surveys in commercial, residential, educational, healthcare and many other building types [15,16]. But as less than 10% of the respondents are facility managers, owners or deconstructors, these trends do not necessarily reflect current use of BIM in existing buildings [15,16].

Although BIM implementation requires profound process changes of the involved parties, the benefits in new construction projects both of private and institutional owners are manifold and often confirmed by involved stakeholders [7,8,17,18]. Major benefits consist in design consistency and visualization, cost estimations, clash detection, implementation of lean construction or improved stakeholder collaboration. Major challenges in new buildings refer to change from design-bid-build processes to integrated project delivery (IPD) and to the increased time effort and knowledge required for BIM use.

BIM implementation in existing buildings however faces other potentials and challenges. Potential benefits of using BIM in FM seem to be significant [11,19,20], e.g. as valuable 'as-built' (heritage) documentation [7], maintenance of warranty and service information [11,19,21], quality control [95,96], assessment and monitoring [7,11,19], energy and space management [11,22], emergency management [19] or retrofit planning [4,19]. Decontamination or deconstruction processes could also benefit from structured up-to-date building information to reduce errors and financial risk, e.g. through deconstruction scheduling and sequencing, cost calculation, rubble management, optimization of deconstruction progress tracking or data management.

Several types of information are necessary to manage a facility or to perform retrofit measures in buildings [11]. Apart from contact and general building information, detailed data on installed components and equipment is needed such as service zones, installation dates, installation type, vendor/manufacturer, geometries and exact location, materials and compositions, physical properties, warranties, as well as maintenance history since completion [11,12]. When building LC draws to a close, further information on occupancy history, actual and detailed (hazardous) material information, components' masses and connections, recycling or disposal options, potential recycling qualities, load bearing structures or deconstruction techniques with associated time and costs per component [2,24] is relevant for deconstruction planning. During a building LC, numerous responsible stakeholders and subcontractors are involved and often withdraw their specialized information e.g. on components' installation [7].

As Building Information Model (BIM) is a tool to manage accurate building information over the whole LC [25], it is adequate to support data of maintenance and deconstruction processes [2,7,24]. As BIM initially was intended to support design and construction processes, some information such as

[3] In this paper, we refer to new buildings as planned buildings, buildings under construction or recently completed buildings.

[4] In this paper, we refer to existing buildings as already but not recently completed buildings.

loadbearing structures is already documented in preexisting BIM while others like LCA information might be added or updated for a required functionality. Since the introduction of international COBie standard, stakeholders are able to store maintenance information in BIM in a structured way and thus in a valuable form of facility documentation [7].
In many existing buildings, incomplete, obsolete or fragmented building information is predominating [11,23]. Missing or obsolete building information might result in ineffective project management, uncertain process results and time loss or cost increases in maintenance, retrofit or remediation processes. As existing buildings often lack as-built documentation due to omitted updating, limitations of BIM use in existing buildings and research challenges are expected.

This paper aims (1) at a comprehensive literature review of BIM creation, implementation and research in existing buildings and (2) at the identification and discussion of current trends and research gaps in this area. The scope includes the specific needs and potentials of BIM for existing residential and non-residential buildings of several ownerships. But it rather disregards considerations on infrastructures and heritage structures, due to their different maintenance requirements and (if necessary) deconstruction processes. The results of this research are useful for industry professionals, BIM developers and researchers involved in the implementation of BIM in existing buildings and structures.
The following section 2 defines BIM in a narrow and a broader sense to assure common understanding of the terminology. Besides, two major BIM creation processes are described. In section 3, examined literature sources and the applied review method is presented. Section 4 focuses on the state-of-the-art BIM creation, implementation and research approaches in existing buildings with regard to functionality, level of detail (LoD), informational, technical and organizational structures in maintenance and deconstruction. Section 5 discusses identified results and research gaps and section 6 concludes our findings.

2 Definition of Building Information Model (BIM)

Building (Construction) Information Model (BIM) is defined by international standards as “shared digital representation of physical and functional characteristics of any built object […] which forms a reliable basis for decisions” [26]. BIMs originate from product models [27,28] that are widely applied in the petrochemical, automotive or shipbuilding industry [7,29]. BIM represents real buildings virtually over the whole LC as semantically enriched, consistent, digital building models [7,30,31]. BIM is realized with object-oriented software and consists of parametric objects representing building components [12,27,32]. Objects may have geometric or non-geometric attributes with functional, semantic or topologic information [7,29]. For example, functional attributes can be installation durations or costs, semantic information store e.g. connectivity, aggregation, containment or intersection information and topologic attributes provide e.g. information about objects’ locations, adjacency, coplanarity or perpendicularity.
BIM can be seen from a narrow and a broader perspective (Figure 1). BIM in a narrow sense (‘little bim’ [33], ‘tool’ [7]) comprises solely the digital building model itself in the sense of a central information management hub or repository [7,30,34,35] and its model creation issues (**technical issues** see section 4.3) [27]. Commercial BIM platforms offer integrated data management, component libraries and general functionalities [7]. Widespread differentiations of BIM are 3D (spatial model with quantity takeoff), 4D (plus construction scheduling) and 5D (plus cost calculation) BIM [7,27]. Further BIM inherent functionalities of dominating vendors are extensively discussed in literature [7,36] and section 4.1.
Different BIM creation processes for new[3] and existing[4] buildings are depicted in Figure 2. For new buildings, BIM is created in a process over several LC stages, starting from inception, brief, design to production (case I) and part of the project delivery. As BIM sometimes is not used by all AEC/FM stakeholders in the building LC yet, some create isolated BIM solely for a designated, single purpose. In existing buildings - depending on the availability of preexisting BIM - BIM can be either updated (case II) [37] or created anew (case III). In Europe, more than 80% of residential buildings are built before 1990 [38] and mainly do not have a building documentation in BIM format [19,39–41].

Therefore if implemented in practice, costly and mainly manual reverse engineering processes ('points-to-BIM', 'scan-to-BIM') (case III) help recapturing building information [42,43].
As depicted in Figure 1, BIM in a broader sense ('BIG BIM' [33,44]) can be divided into interrelated functional, informational, technical and organizational/legal issues. Depending onto the stakeholders needs and the project requirements, a BIM model is used to support and perform expert services for buildings such as energy or environmental analyses [7]. Therefore, two types of expert software might interact with a BIM model: (1) data input applications providing services of import, data capture and monitoring, data processing or transformation of captured data into BIM or (2) data output applications providing reports or technical analyses such as structural and energy analyses or clash detections (see also Table 3).

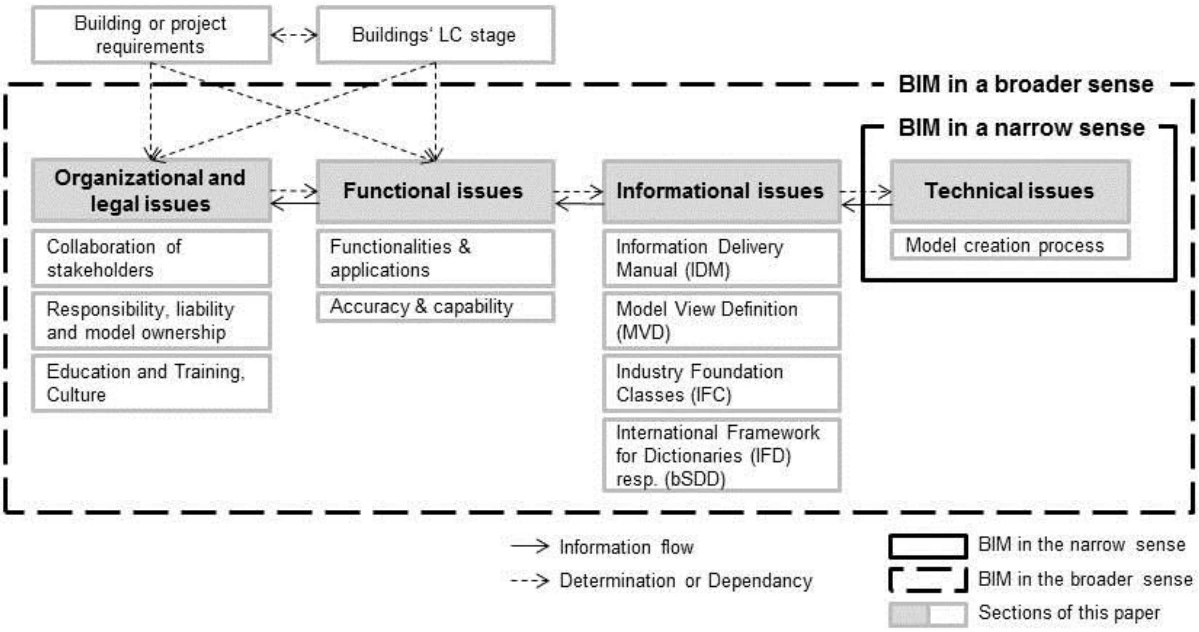


Figure 1: Relations between LC stage as well as functional, informational, technical and organizational issues of BIM, partly according to [8,17]

In this paper, we refer to BIM functionalities (**functional issues**, see section 4.1) as services or capabilities that are provided by BIM in the narrow sense or its accompanying data output software. This data output or functionality depends on stakeholder and building or project requirements as well as on the buildings' LC stage. On the other hand, functionalities determine informational or organizational issues e.g. with respect to data exchanges or communication processes. This relationship becomes evident within the following example: if e.g. an energy analysis of a building is required, specific information is needed (e.g. U-values of components, radiation level or orientation of the building) to perform the analysis. If this information is not inherent in the narrow BIM model, a structured data exchange between BIM model and expert functionality has to take place. Organizational and legal structures (roles) determine the access to and define responsibilities for input and analysis data and their correctness.
Depending on the required functionality, a suitable informational structure and data exchange (**informational issues,** see section 4.2) with the model is necessary to guarantee interoperability between different software systems without information loss. Functional and informational requirements again determine model characteristics (**technical issues,** see section 4.3) through LoD, required model capacities and consequently required model creation processes. **Organizational and legal issues** (see section 4.4) determine the stakeholder roles, their information rights and liabilities, their model access (read, write) or their obligation to provide a special functionality or data output.

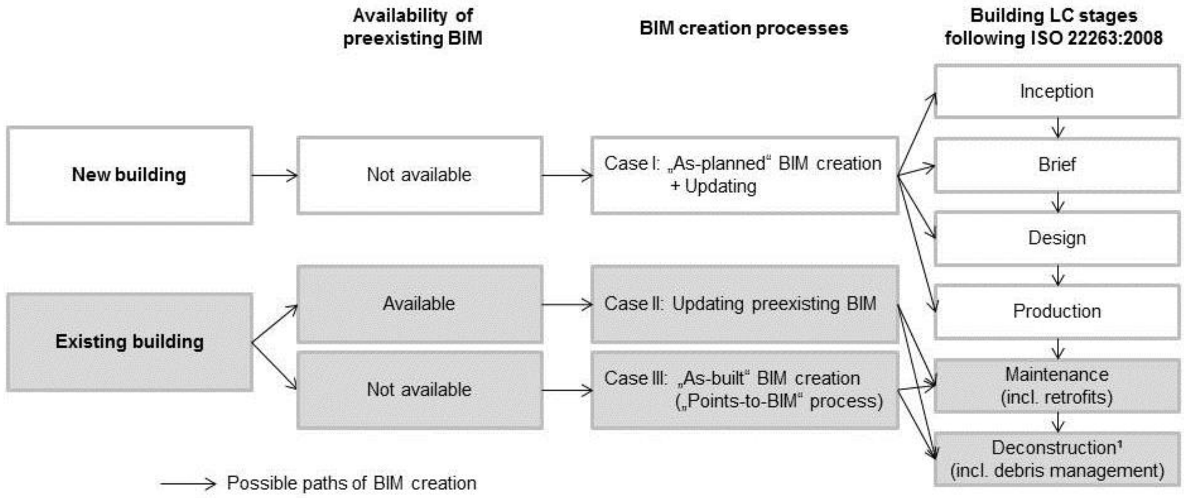


Figure 2: BIM model creation processes in new or existing buildings depending on available, preexisting BIM and LC stages with their related requirements [45,46]

3 Review approach

3.1 Originality

In literature, numerous reviews of BIM implementation and research approaches in new buildings [7,8,17,27,29,47,48] predominate, while BIM usage in existing buildings is rather neglected yet [11,19]. Existing reviews either cover one or two aspects separately or concentrate on few cross-sectional challenges. Functional issues in the areas of maintenance [7,11,12,14,20,45,49–56] and deconstruction [2,24] are addressed separately and mainly for new buildings (see Table 3). Also, informational [26,27,50,57–60], technical [19,31,40,43,45,61–66] and organizational/legal [21,67] issues of BIM use are often examined separately. Publications on informational issues mainly consider new buildings' requirements, whereas the publications on technical issues focus either on capturing construction data or geometries of existing buildings for processing into digital building models [19,31,62]. Papers with regard to organizational/legal issues concentrate on collaboration of consortia partners in new building projects and in facility management (FM).

Publications with a broader scope considering more than one of the previous issues [6,68,69] (e.g. LoD in BIM) and covering several BIM issues [7,8,17,27] mainly for new buildings are sporadic. Publications explicitly devoted to BIM for existing buildings, especially without preexisting BIM and discussing related research challenges, are rare [19].

Questionnaires on BIM implementation status and benefits are quite constantly conducted [8,11,15–17,47,48]. But surveys do not focus on post-construction stakeholders, processes and related issues yet. Less than 10% of the respondents are owners, facility managers or deconstructors, while the majority originates from the disciplines of architecture, cost calculation, construction or project management [15–17]. Thus, these surveys do not provide representative statements on usage, hindrances and major trends of BIM in existing buildings.

As to our knowledge there is no comprehensive overview of recent research of BIM for existing buildings, we partly try to close this gap with the contribution at hand. The objective of this paper is to examine BIM in a broader sense, as depicted in Figure 1, and to analyze the required BIM functionality in existing buildings as well as the influential dependencies between informational, technical and organizational issues of BIM. Also, specific or multidisciplinary research gaps are identified and discussed.

3.2 Methodology

To review BIM for existing buildings comprehensively, our three-step approach examines both academic and applied publications [17].

In a first step, journals in academic and applied databases[5] are identified that contribute to BIM implementation or LC stage-dependent BIM functionalities in existing buildings. The found journals either focus on (1) built environments and its processes (AEC/FM) partly integrating sustainability issues, (2) information technology application in the construction sector, (3) remote sensing technologies, surveying and computer vision or (4) LC considerations and rubble management (see Table 1).

Table 1: Examined Journals, classified according to their scope

Scope	Journals (Publisher)	#
Built environment (AEC/FM)	Archives of Civil and Mechanical Engineering (ELSEVIER) Automation in Construction (ELSEVIER) Building and Environment (ELSEVIER) Building Research & Information (T&F) Built Environment Project and Asset Management (EMERALD) Construction and Building Materials (ELSEVIER) Construction Innovation: Information, Process, Management (EMERALD, EBSCO) Engineering, Construction and Architectural Management (EMERALD, EBSCO) Engineering Structures (ELSEVIER) Facilities (EMERALD) International Journal of Sustainable Built Environment (ELSEVIER) International Journal of Urban and Regional Research (WILEY) Journal of Building Information Modeling (NBIMS and NIBS) Journal of Construction Engineering and Management (ASCE, EBSCO) Journal of Engineering, Design and Technology (EMERALD) Journal of Engineering Mechanics (ASCE) Journal of Facilities Management (EMERALD) Journal of Information Technology in Construction (CIB) Journal of Structural Engineering (ASCE) Smart and Sustainable Built Environment (EMERALD) Structural Survey (ELSEVIER) Structure & Infrastructure Engineering: Maintenance, Management, Life-Cycle Design & Performance (T&F)	22
Civil Engineering Informatics	Advanced Engineering Informatics (ELSEVIER) Advanced Engineering Informatics with Engineering Applications of Artificial Intelligence (ELSEVIER) Advances in Engineering Software (ELSEVIER) Computer-Aided Civil and Infrastructure Engineering (WILEY) Computer Methods in Applied Mechanics and Engineering (ELSEVIER) Engineering Analysis with Boundary Elements (ELSEVIER) Journal of Computing in Civil Engineering (ASCE) Journal of Systems and Information Technology (EMERALD) Multidiscipline Modeling in Materials and Structures (EMERALD)	9
Remote Sensing, Surveying, Computer Vision	International Journal of Computer Vision (SPRINGER) ISPRS Journal of Photogrammetry and Remote Sensing (ELSEVIER) Journal of Surveying Engineering (ASCE) The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS) The Photogrammetric Record (WILEY)	5
LC & waste management	International Journal of Life Cycle Assessment (SPRINGER) Resources, conservation and recycling (ELSEVIER) Waste management (ELSEVIER)	3

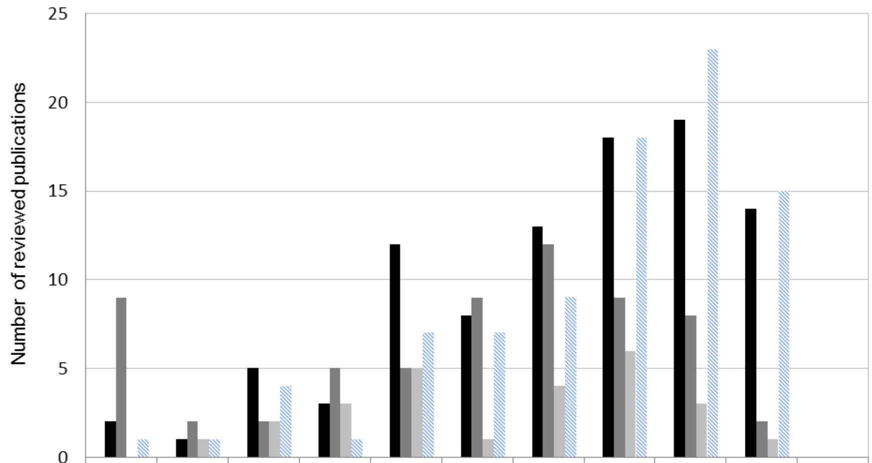
In order to limit this broad scope in a second step to LC stages of maintenance and deconstruction, we perform a keyword search in the aforementioned academic journals as well as in databases and conference proceedings. Main keywords are 'BIM', 'building (information) model', 'existing buildings', 'maintenance', 'facility management', 'retrofit' and 'deconstruction'[1]. With this standard practice in academic literature review we receive a comprehensive picture of recently published research and implementation efforts. Besides, to consider actual developments beyond academic publications we reviewed applied publications of relevant stakeholders such as professional associations (e.g. ASCE

[5] Journal databases: www.elsevier.com, www.emeraldinsight.com, www.sciencedirect.com, www.ebscohost.com, www.link.springer.com, www.tandfonline.com, www.onlinelibrary.wiley.com, www.asce.library.com and others; Conference proceedings: 3D(IM)PVT, CIB, CRC, ICCCBE (ASCE), ISARC, ISPRS, SASBE, SB and other conferences on data processing, computer vision or building modeling.

and their journals), of standard committees (e.g. buildingSMART, openBIM), of software solution providers (e.g. ASI) and of state authorities. Within the found publications, we further differentiated between publications mentioning or not mentioning ‘BIM’ in keywords or abstract (see Figure 3 and Figure 4).
Due to the applied method, the review excludes research currently underway that is not available in mentioned databases, or studies which have not been published in English yet.

3.3 Data analysis

Over 180 publications (books and academic/applied papers) and relevant standards and internet sources were reviewed, thereof 90 journal papers, 63 conference papers and 26 other publications (e.g. books or papers in applied journals). As Figure 3 shows, over 80 of the reviewed publications are explicitly devoted to BIM (‘BIM’ in abstract or key words). The remaining publications nevertheless are relevant: some either (1) do not mention BIM in its keywords or abstract, although addressed in the publication, or (2) regard 3D building models that are not explicitly BIM, partly due to unclear definition, e.g. models that lack semantic information or parametric representation of components (such as surface, BREP, CSG or CAD models), or (3) deal with related topics, such as cloud computing or semantic web services. It also becomes clear from Figure 3, that most BIM papers were published after 2008 with a considerable intensification in the latest years.



	<2005	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Total of reviewed publications	11	4	9	11	22	18	29	33	30	17	184
■ … thereof journal papers	2	1	5	3	12	8	13	18	19	14	95
■ … thereof conference papers	9	2	2	5	5	9	12	9	8	2	63
■ … thereof other type of publication	0	1	2	3	5	1	4	6	3	1	26
… thereof with 'BIM' in keywords or abstract	1	1	4	1	7	7	9	18	23	15	86

Figure 3: Frequency of reviewed publications per year of publication

Figure 4 presents different topics (see also Table 2) associated with BIM in existing buildings in relation to their year of publication. Several recent trends become obvious:

- The trend of BIM publications continues unabated and the range of published topics increases significantly.
- Topics of research areas like data management, documentation, controlling and progress tracking or measurement are published with almost constantly raising tendency.
- Demolition/Deconstruction planning in the context of BIM is a novel area of research.

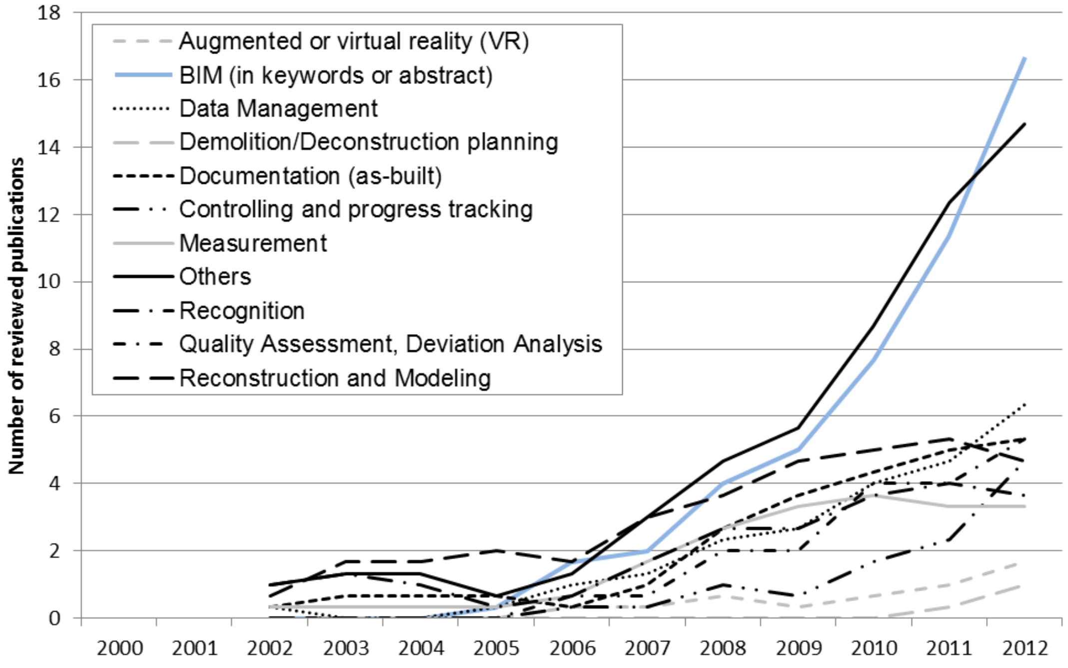


Figure 4: Number of reviewed publications with designated BIM topics per year (multiple naming possible), depicted with moving average on 3 periods

Table 2 displays the frequency of major LC stages, topics and spatial foci in the reviewed journal and conference papers. In total, most publications deal with BIM creation and modeling and respectively with existing buildings' exteriors. Fewer papers deal with maintenance aspects of data management and "as-built" documentation, quality assessment/deviation analyses and survey/measurements accuracy on building component level. Only few research approaches discuss deconstruction functionalities in BIM in conference proceedings of ASCE 2012 and ICCCBE 2012 [2,24]. A third paper in this area focuses on rubble management through RFID [70]. Related to the total amount of reviewed papers, on average each paper covers 1.7 areas of contribution. Spatial foci of the reviewed papers are mainly on the buildings' exterior or interior, followed by building components.

4 Implementation and research approaches of BIM in existing buildings

In this section, BIM in a broader sense is described with its functional, informational, technical and organizational/legal issues in building maintenance and deconstruction. Apart from depicting state-of-the-art implementation, we present current research approaches and identify future areas of research.

4.1 Functional issues

4.1.1 Functionalities and applications

Due to numerous design, engineering, construction, maintenance and deconstruction services during building LC, potential applications and required functionalities of BIM in buildings and infrastructures are manifold. Depending on the stakeholders' and project requirements, BIM with e.g. architectural, constructional, piping and electrical, structural, fabricational or monitoring functionality is needed.
Functionalities are either inherent in 3D, 4D or 5D BIM (e.g. quantity takeoff, scheduling or cost calculation) or they are attached to BIM as independent expert applications. Expert functionalities use the underlying BIM data to support, extend, calculate or simulate specific business requirements (e.g. perform structural analyses). Results are either reintegrated into BIM or reported separately. Functionalities are based on process maps, which describe the logical flow of information and activities as well as the stakeholders roles within a particular functionality [26].

Table 2: Frequency of different LC stages and topics in 184 reviewed publications (multiple naming possible)

Scopes		**Number of reviewed publications**
Publications focusing on building LC stages of …	Design (incl. inception and brief)	43
	Construction (incl. planning, scheduling)	59
	Maintenance (incl. retrofits, monitoring)	109
	Deconstruction (incl. planning, execution)	10
	Others (e.g. prefabrication)	26
	Total	**247**
	Average of LC stages per paper	**1.3**
Publications with contributions in…	BIM creation and modeling	40
	Data management	36
	Documentation ('as-built')	36
	Survey/Measurement accuracy	27
	Quality assessment, deviation analyses	26
	Object recognition	25
	Monitoring or progress tracking	18
	Augmented/Virtual reality	10
	Demolition/Deconstruction management	3
	Others	83
	Total	**304**
	Average of topics per paper	**1.7**
Publications with spatial focus on…	Building exterior (e.g. facades, roof)	63
	Building interior (e.g. rooms)	58
	Building components	43
	Building supporting structure (e.g. walls, slabs)	26
	Infrastructure	14
	Others (e.g. street views, city models)	20
	Total	**224**
	Average of spatial foci per paper	**1.2**

Table 3: Examples for major applied or developing BIM functionalities for existing buildings

Functionality	**Research**	**Practice**
Clash detection, Spatial program validation, BIM quality assessment	[7,71]	[7,57,72,73]*
Construction progress tracking	[7,45,61,74–83]	-
Cost calculation or Cash flow modeling (5D)**	[7,17,55,84–87]	[57,72,88–90]
Daylight simulation	[91]	[92,93][92][94]
Deconstruction, Rubble management	[2,24]	-
Deviation analysis, Quality control, Defect detection	[4,25,45,62,69,94–98]	-
Documentation, Data management and Visualization	[7,12,20,23,68,75,76,99]	[7,100–102]
Energy/Thermal analysis and control, Carbon foot printing	[7,22,60,86,103–105]	[57,106–109]
Localization of building components, Indoor navigation	[11,20,70,110–112]	-
Life cycle assessment (LCA), Sustainability	[10,11,22,29,113–116]	[108]
Monitoring, Performance measurement (through sensors)	[23,117–119]	[120]
Operations and Maintenance (O&M), Facility management (FM)	[7,11,12,14,20,45,49–56]	[13,102,121–129]
Quantity takeoff (3D)	[7]	[57,72,88]*
Retrofit/Refurbishment/Renovation planning and execution	[3,11,130–132]	-
Risk scenario planning	[17,87]	-
Safety, Jobsite safety, Emergency Management	[133–142]	-
Scheduling (4D)	[7,17,55]	[72]
Space Management	[11,104,143]	-
Structural analysis	[140,144,145]	[146–149]*
Subcontractor and supplier integration, Prefabrication (e.g. of steel, precast components, fenestration, glass fabrication [7])	[7,55]	[7]

* available in every major BIM software [7] ** often country-specific

Table 3 displays major examples of inherent and expert functionalities applied in practice and examined in research. Currently, research rather focuses on expert functionalities for new buildings, such as energy and carbon reduction analyses, construction progress tracking (matching of captured data with preexisting BIM), deviation analyses (quality control, defect detection) and jobsite safety. According to BIM's original application in new construction, applied functionalities concentrate on design and visualization, procurement, manufacturing, construction management and coordination rather than on commissioning, facility management or deconstruction. But recently, planning and handover processes shift from design-bid-built to integrated project delivery (IPD) in a collaborative atmosphere [15], considering the value of "as-built" BIM information for FM, retrofit and deconstruction processes.

As new construction rates in industrialized countries stagnate, planning and implementing refurbishment and retrofit measures in existing buildings gain in importance [3]. Various digital tools for building capture and auditing are available, such as 2D/3D geometrical drawings, tachometry, laser scanning or automatic locating of images, but need increased modeling and planning efforts of skillful personnel [3,35,130]. Existing maintenance functionalities - so called Computerized Maintenance Management Systems (CMMS) or Computer Aided Facility Management (CAFM) - focus on (web-based) data management, maintenance schedules and equipment warranties of increasingly complex buildings [23,99], but they are intensely developed [11,150] e.g. with respect to deterioration and cause-effect relationships [99]. Partly, FM systems include laser scanning of existing facilities and bidirectional information flow between Geographic Information Systems (GIS) and maintenance data [124,127]. While there are many research efforts in FM and BIM related topics, an industry-wide implementation is lacking yet [11]. But case studies show reasonable results e.g. in Sydney Opera House [13], campus buildings [4,20] and other facilities [7].

Most of the mentioned FM, refurbishment and deconstruction research approaches require an available BIM of a recently constructed building [3]. If a BIM of the designated structure exists, the functionalities and processes of planning and performing conversions, refurbishments and deconstructions might be performed with smaller adjustments. But if only an outdated or no BIM is available, processes start with building auditing, documentation review and analyses of previous and current building properties [3,130] to provide a profound basis for planning and cost estimating. This area is intensely researched [31,62,130,151–153] and focus of section 4.3.

Although digital costs estimation, quantity take-off, data management and reporting tools are used in deconstruction industry, BIM functionalities of deconstruction [2,24], vulnerability and collapse analyses [146,154], emergency management [141], localization or documentation of hazardous or contaminant materials [2,30] or risk scenario planning [17] are rare in literature yet. Besides, other potential BIM functionalities are not covered yet like deconstruction execution planning and progress tracking, recycling and rubble management, secondary component and raw material auctions, recycling network logistics, monitoring of hazardous components or automated reporting to authorities. One reason might be the low participation of facility managers, retrofitters and deconstructors in the development of BIM functionalities [15]. Another reason might result from COBie and OmniClass standards, that define several properties and attributes to support maintenance processes [53,124,155], but only partly enable deconstruction and recycling functionalities (e.g. with demolition date, recycled date, ease of relocation or removal, material properties). The analysis of OmniClass properties (Table 49: Pre Consensus Approved Draft from 2012-10-30) showed, that many properties defined for manufacturers and their processes could easily be adapted to deconstructors requirements e.g. deconstruction lead and idle times, deconstruction and shipping costs, deconstruction and recycling methods or source limitations for deconstructors (see also Table 4). But deviations, damages or deterioration effects are not depicted yet and need further research [99,130].

Table 4: Literature and own suggestions of IFC attribute extensions to describe inaccuracies, uncertainties or future processes and treatments occurring in existing buildings [2,7,35,62,69,79,82,99,130,156]

Areas	Potential IFC attribute extensions (main category)	(subcategory)
Existing building audits and surveys	Uncertain/lacking information in captured data	• Clutter, measurement errors
	Vegetation and site conditions	• Trees, shrubbery etc. • Ground conditions like sloping ground
	Uncertain/lacking information on BIM objects	• Damages, defects or deterioration of building elements • Deviations in geometric or topological object information like uneven floors/walls or non-orthogonality; • Concealed and thus assumed components and components' physical properties like detailed layers, structure or (hazardous/contaminant) material composition
	Uncertain/lacking information on BIM relations	• (Non-)loadbearing structures, containing relation, adhering relation etc.
Maintenance- and Deconstruction-related information	Location properties	• Locations of sorting, recycling/reprocessing and disposal facilities, temporal storage facilities
	Properties of time and money	• Deconstruction lead and idle times • Deinstallation/dismantling costs • Object treatment costs e.g. for reinforcement, repair, decontamination, reprocessing, recycling, disposal • Shipping costs to recycling/disposal facilities or other construction sites
	Source properties	• Source limitations for deconstructors and decontaminators like required operating and storage spaces • Methods of deconstruction or recycling • Equipments with their characteristic durations, costs, resources (personal, machines) • Dependencies and precedences in maintenance and deconstruction processes • Deconstructors' certifications • Consultant and authorities' properties, e.g. information requirements
	Product properties	• Disassembly types and groups • Possible future or performed object treatments e.g. reinforcement, repair, decontamination, reprocessing, recycling, disposal options • Structural behavior during deconstruction • Properties of sustainability, e.g. recycling material quality, recycling and disposal rates of building components, hazardous materials
	Process planning	• Safety plans and prevention measures or deconstruction progress tracking
	Possible future emissions	• Noise, dust or vibration emissions from deconstruction processes or other emissions according to LCA information with related prevention measures and costs

As described functionalities require accurate information on objects, relations and attributes in BIM, maintenance and updating of information in BIM remains a major challenge and area of research [11,21]. Due to long lifetimes of buildings and infrastructure, recent research also adresses BIM model evolutions, continuous model maintenance and management of temporal data [12] as well as the interoperability with developing BIM and expert software [11,37] (see also section 4.2).

4.1.2 Accuracy and capability

BIM functionalities require a certain accuracy, information richness and actuality of the underlying data to fulfill their purposes [6,7]. A frequently mentioned concept to describe information richness of BIM objects is 'Level of Detail' or also referred to as 'Level of Development' (LoD). LoD defines geometric and non-geometric attribute information provided by a model component [157,158], often referenced to a point of time, LC stage or to a contractual responsibility. To enable e.g. analysis or scheduling functionalities, the required LoD of objects' attributes and relations has to be defined, such as durations, dependencies or precedence information. Some LoD in literature are depicted in Table 5, whose definitions differ in geometric accuracy, quality or completeness of semantic information [71,152].

Table 5: Levels of Detail / Levels of Development (LoD) in BIM models according to literature

Levels of Detail	Approximate geometry, Precise geometry, Fabrication level/construction documentation	[6]
	Conceptual, Approximate geometry, Precise geometry, Fabrication, As-built	[159,160]
	As-designed/As-planned, As-built, As-used	[71,152]
	Schematic design, Detailed design, Level of fabrication (shop model)	[7]
Levels of Development	LOD 100, LOD 200, LOD 300, LOD 400, LOD 500	[44,158]

In new construction projects, LoD increases in the course of LC stages from inception to production/construction depending on the changing requirements and refinements from draft to realization. In literature, functionality-related LoDs are defined for general modeling [31], 3D imaging [161] and energy performance [162]. In existing buildings, required functionality determines the LoD and the resulting cost and effort associated with BIM creation [6]. For maintenance functionalities, the Construction Operations Building information exchange (COBie) standard defines a LoD for technical equipment, regarding type and location, make, model and serial numbers, tag, installation date, warranty and scheduled maintenance requirements [155] (see also section 4.2.2). Klein et al. [43] define 2% geometric deviation for maintenance applications but do not provide a LoD of non-geometric information. For deconstruction functionalities (incl. rubble management) no adequate LoD is defined yet.

Beyond LoD, several BIM assessment frameworks are under development, such as CMM[6], CMMI, P-CMM, Object/Element Matrix or ISO/IEC 15504 (SPICE) [155,159,160]. As ISO/IEC 15504 generally formulates the process assessment, the Capability Maturity Model (CMM) is used in BIM contexts to evaluate if BIM projects or processes reach the desired level of functionality [163]. CMM assessment framework formulates minimum capabilities and requirements of BIM model and process maturity [163] with ten levels of BIM maturity defined for categories of: Spatial Capability, Roles/Disciplines, Data Richness, Delivery Method, Change Management or Maturity Assessment, Business Process, Information Accuracy, Lifecycle Views, Graphical Information, Timeliness and Response as well as Interoperability and Industry Foundation Class Support.

Professional associations try to define and harmonize related concepts and ratings measuring BIM's data requirements and capabilities, but yet there has not emerged a standard assessment framework of BIM for both new and existing buildings [160,163].

4.2 Informational issues and interoperability

Expert functionalities are linked with a BIM model through Information Delivery Manual (IDM) frameworks and Model View Definitions (MDV) providing relevant information, facilitating data exchange and avoiding ambiguities [59]. As shown in Figure 5, IDM frameworks and MVD specify storage, conversion and information exchange in BIM and thus form the link between functional, technical and organizational issues. The exchange requirement model (ERM) describes the information flows with regard to: the requesting users in their roles, the relevant information for a designated process, the moment of the information flow, the content and the receiving user/role. Non-

[6] The Capacity Maturity Model defines a minimum of information in BIM according to the following categories: Spatial Capability, Roles or Disciplines, Data Richness, Delivery Method, Change Management or ITIL Maturity Assessment, Business Process, Information Accuracy, Lifecycle Views, Graphical Information, Timeliness and Response, Interoperability and Industry Foundation Class Support [163]

proprietary standards like Industry Foundation Classes (IFC) (ISO/PAS 16739) [165] and International Framework for Dictionaries (IFD) (ISO 12006-3) [183] enhance data exchange between different BIM systems on object level minimizing information loss. Also, initiatives like UniClass and OmniClass further structure and unify the information content of organizational roles, project phases, services or component properties. The following sections depict the related informational issues in more detail.

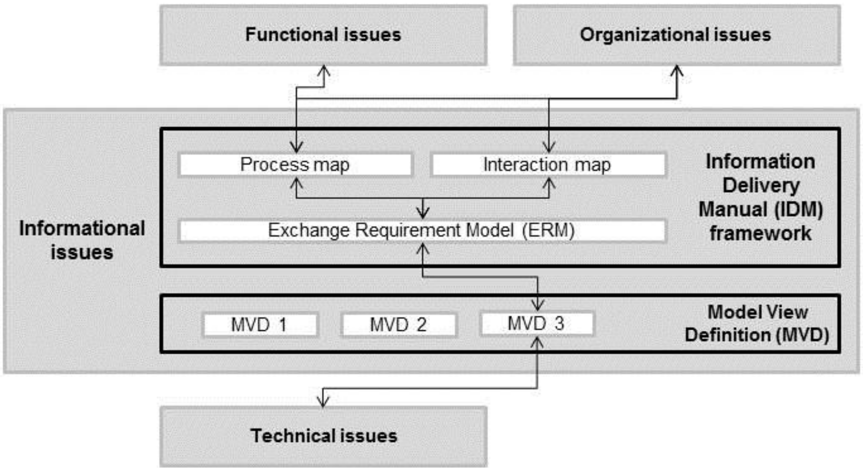


Figure 5: Information Delivery Manual (IDM) framework (ISO 29481-1:2010) [26] and its relations to functional, technical and organizational issues in BIM

4.2.1 Information Delivery Manual (IDM) framework

The IDM framework defines the functionality-related exchange of process information in BIM through process maps, interaction maps and the associated Exchange Requirement Model (ERM) [166]. Process maps describe the flow of activities within a particular topic, the actors' roles and information required, created and consumed, while interaction maps define roles and transactions for a specific purpose or functionality [26]. The ERM is the technical solution defining a "set of information that needs to be exchanged to support a particular business requirement" [26] or functionality and is interrelated with MVD [26]. In literature, an IDM framework for energy analysis is presented in [167]. But for maintenance or deconstruction processes IDM frameworks are not defined yet [166].

4.2.2 Model View Definition (MVD)

A Model View Definition (MVD) or IFC View Definition defines "a subset of the IFC […] that is needed to satisfy one or many Exchange Requirements of the AEC industry" [58]. A MVD structures relevant information for efficient information flow between stakeholders in building-related processes or for e.g. energy or structural analyses. MVD definition depends on the required functionality and the referred BIM objects and attributes in process and interaction maps [59,168].

For maintenance purposes, COBie is the predominant, vendor-neutral, international standard MVD to exchange contact and general facility information as well as information about spaces, floors, zones, components, technical systems and equipment [51,57,58,169,170]. Newly, this standard is complemented by a responsibility matrix that allots the kinds of required data to the responsible persons or roles [171]. As COBie contains general building information, spaces/zones, and information on equipments such as their geometries, locations, certificates and warranties, performance data and testing results, preventive maintenance, safety and emergency plans or start-up/shut-down instructions [11,172], it can be seen as a core model accompanied and extended by domain-specific exchange requirements. E.g. the extension of WSie is planned to provide performance information about piping connections, flow rates or other controlling information [173]. MVD for other domain-specific functionalities are depicted in Table 6. As many MVD refer to new buildings' requirements, the listed MVD are only partly relevant and adequate in maintenance processes, due to differing requirements and information structures. Besides, so far there is no publication defining MVD for audits of existing buildings [130] (e.g. with respect to structural and inventory survey) or MVD for deconstruction, recycling or rubble management processes and functionalities in BIM yet.

Table 6: Exemplary Model View Definitions (MVD) for BIM functionalities in IFC2x3 format; others can be found in [168]

Model View Definitions (MVD)	Acronym	Literature
BIM Service interface exchange, (web services and server-client communication)	BIMSie	[174]
Building Automation Modeling information exchange (control and building automation systems)	BAMie	[175]
Electrical System information exchange (delivery of electrical power within facilities)	Sparkie	[176]
Equipment Layout information exchange	ELie	[172]
IFC2x3 Coordination View Version 2.0 (optional with Quantity Takeoff, Space boundary or 2D Annotation add-on view)	-	[58]
IFC2x3 Structural Analysis View (released)	-	[58]
HVAC (Heating, Ventilation, Air-conditioning, Cooling) information exchange	HVACie	[177]
Life-Cycle information exchange, with the refinement of Building Programming information exchange	LCie, BPie	[171,178]
FM Basic Handover with Construction-Operations Building information exchange	COBie	[50,57,58,169,172]
Quantity Takeoff information exchange	QTie	[57]
Spatial validation	-	[57]
Water System information exchange	WSie	[173]

4.2.3 Industry Foundation Classes (IFC)

Data exchanges are possible either directly, or through proprietary or non-proprietary exchange formats [7]. IFC defined in ISO/PAS 16739:2005 [165] is the dominant non-proprietary exchange format of building information between AEC/FM software [7,27,67,179]. It was developed to represent building information over the whole buildings' LC (except deconstruction) [7,180] and to facilitate data transfer between BIM modeling software (e.g. Autodesk or Bentley), IFC viewers (e.g. IFCStoreyView) and expert software applications (e.g. 'Model Checker' from Solibri). Data exchanges between source and receiving software systems are performed through mainly proprietary translators with own data structures [7]. Certifications like 'openBIM' of buildingSMART and NBIMS award software solutions with high IFC interoperability.

Interoperability of BIM in different LC stages and functionalities still is limited [27,48] due to incomplete, differently or ambiguously used IFC attributes, denotations or contents [30,34,59,181] (see section 4.1.1). Often, one-way interfaces from BIM model to expert applications are used [7]. Recent developments focus on the implementation of Specifiers' Properties[7] Information Exchange (SPie) and semantic web technologies in open formats and ontologies like HTML, XHTML, bcXML, gbXML, e-COGNOS, COBie, IFCXML, IFC, ifcOWL or CIS/2 to enable expert software applications [7,60,179,182]. But most applications restrict to academic use yet [179].

4.2.4 International Framework for Dictionaries (IFD) Library respective buildingSMART Data Dictionary (bSDD)

The International Framework for Dictionaries (IFD), defined in ISO 12006-3 [183,184] and recently renamed in buildingSMART Data Dictionary (bSDD), is a terminology standard for BIM libraries and ontologies [185]. It is an object-oriented database of multi-lingual terms which define concepts used in the construction industry [181] and respective IFC characteristics, such as denotations of objects, parts, attributes, units or values. Regional adaptations and customization of IFC are possible due to globally unique ID (GUID) tags defined of an international working group [181]. IFD supports interoperability of BIM content through GUID between BIM and project or product specific data [184,185].

Standards ISO 12006 parts 2 and 3 structure BIM content, while OmniClass™ specifies BIM content according to AEC requirements into construction results, construction resources and construction processes [186]. A profound analysis of OmniClass properties revealed that some properties for representing existing buildings and related processes are lacking yet (see Table 4 in section 4.1.1).

[7] BIM objects' properties and attributes are used synonymously.

Future challenges remain the assignment of attributes to LC stages [185–187], to MVD and to process interfaces [7].

4.3 Technical issues

As BIM in a narrow sense is modeled to fulfill required functionalities [153,188] for example in maintenance or deconstruction, technical issues depend on the LoD required by the designated functionality. Therefore when applied to existing buildings, the functionality-related LoD determines the technical specifications of data capture, processing and BIM model creation. The BIM creation process can be differentiated between for new and for existing buildings due to varying building information quality, information availability and functionality requirements (see Figure 2). For new buildings, model creation of the "as-planned" BIM is done in an interactive, iterative process with commercial design or planning software (Figure 6 – left part) and allows updating to an "as-built" BIM (case I). Since many existing buildings have rather insufficient, preexisting building documentation either preexisting BIM is updated (case II) [37] or a "points-to-BIM" process is performed (case III) [4,43,62,68] to gather and model actual building conditions (Figure 6 – right part). To create an as-built BIM from scratch (case III), geometrical and topological information of building elements has to be gathered, modeled and complemented by semantic property/attribute information manually. If a reliable data capture technique could provide an as-built BIM at reasonable time and cost [19,42,62,65,152,153], existing buildings could benefit from BIM usage e.g. regarding documentation, visualization or facility management.
The three cases differ considerably in potential modeling effort. In most existing buildings, insufficient building information and no available preexisting BIM lead to application of case III which is discussed in further detail below.

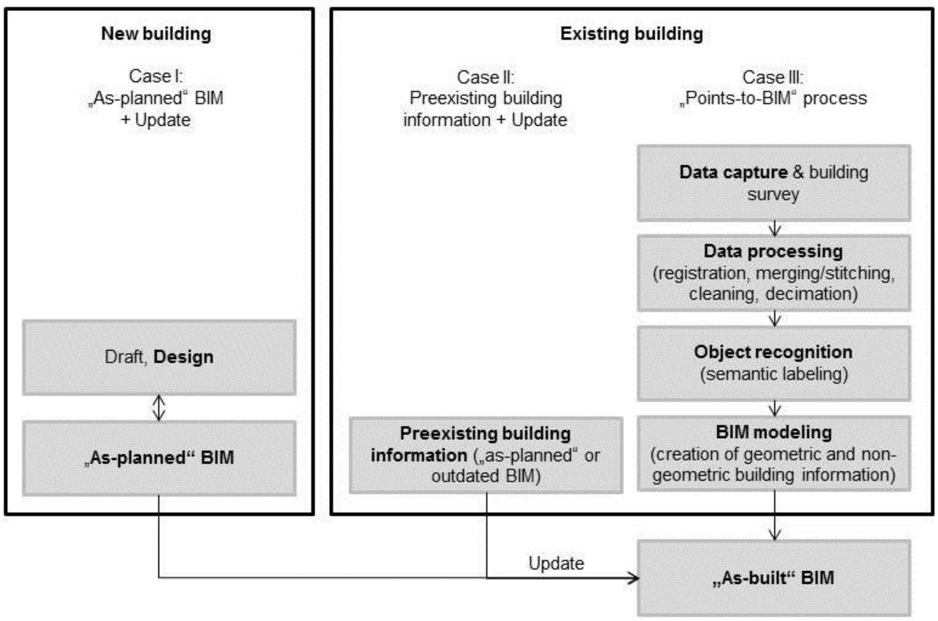


Figure 6: BIM creation processes for new and existing buildings, partly from Huber et al. [62]

4.3.1 Data capture

If building information is insufficient for required functionalities, techniques of data capture[8] or survey are applied [35]. The required LoD determines all following steps from technique selection to model creation due to its great influence on required data quality, data volume and processing effort.

[8] Synonyms: data capture, data acquisition, data retrieval. However, building survey implies measurements from building components.

Figure 7 shows non-contact techniques further differentiated into image-based, range-based, combined or other techniques; contact methods consist of manual or other techniques [39,189,190]. Image- and range-based techniques extract mainly spatial, color and reflectivity information. In practice, semi-automated laser scanning with total stations is prevalent [153], although affected with disadvantages such as high equipment cost and fragility as well as difficulties in scanning reflective, transparent and dark surfaces [43,61]. Besides, this technique needs further extensive data processing and modeling steps (see following sections) on conventional computers and current approaches have rather minor LoDs [4,30,31,52,66,130,151,191,192].

Manual techniques capture mostly spatial and other component-related information. Few approaches focus on other techniques like tagging [110,111,193] or utilize preexisting building information [25,130,194] to gather additional information such as components' dimensions, materials, textures, functions, connections, positions or maintenance periods. RFID or barcode tags are rather installed in new buildings [7,70,195], because in existing buildings tagging is limited by installation effort (e.g. to retrofits), readability range and interoperability [110,111,193].

Table 7 summarizes the major data capturing techniques of laser scanning, photogrammetry and tagging that are relevant in research [19,31,40,43,61,77,151,196] and decisive features for technique selection. Main characteristics are cost, time, LoD and environmental conditions during data capture (e.g. light, weather, vegetation, concealments, clutter). Combinations of techniques are common and try to overcome drawbacks of individual capturing techniques [25,63,83,190,197–199]. In practice, laser scanning is widely applied to measure infrastructures' and buildings' dimensions [79,94,200], and to record and update city surfaces [201].

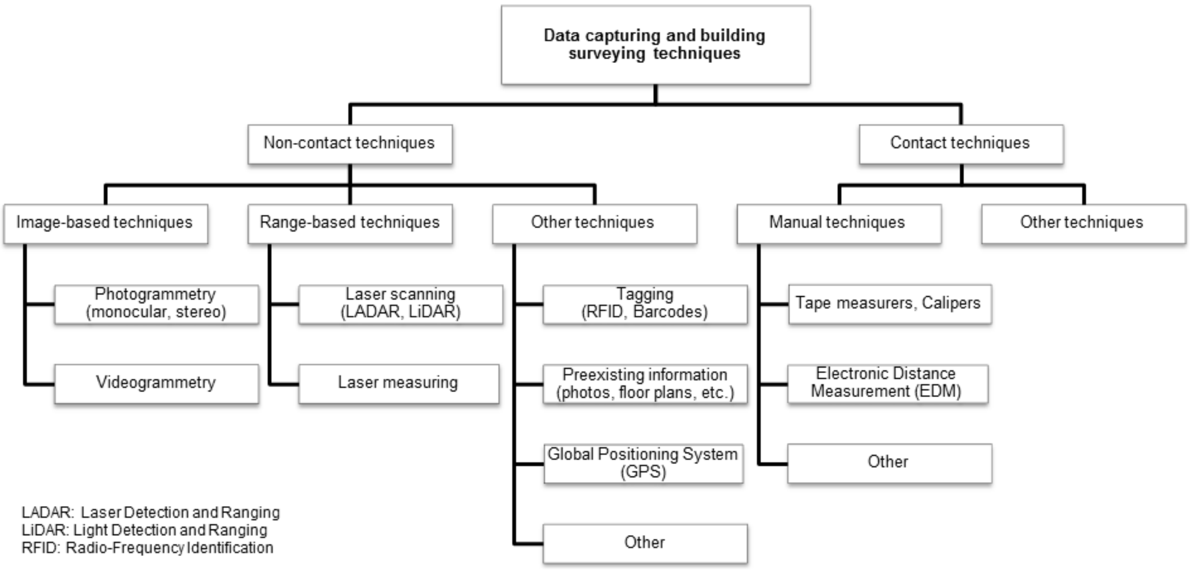


Figure 7: Systematic overview of data capturing and surveying techniques to gather existing buildings' information [7,19,45,61,78,189,202]

Maintenance functionalities require a high LoD of components, the installed equipment, services and appliances [50]. Therefore, tagging is rather inadequate for application in maintenance in terms of spatial accuracy, LoD and degree of automation. Time and cost restrictions are major decisive features [2] in deconstruction processes, but a related LoD and appropriate capturing technique is yet to be defined.

Recent research focused on capturing mainly geometric rather than semantic representations of buildings and feeding point cloud data into BIM software [4,19,43,152,199,203–210]. But new developments intensely research process models for automated BIM modeling from captured data ('scan-to-BIM') and improvements in LoD [31,151,192] to enhance application in existing buildings. In order to perform a comprehensive audit on existing buildings, the mentioned data capturing techniques might be combined with other methods of non-destructive testing to analyze materials and properties. Possible methods could include material- or texture-based recognition [151] and structure recognition beyond surface through ground penetrating radars, radiography, magnetic particle inspection, sonars or electro-magnetic waves [205] or tags installed during retrofits.

Table 7: Characteristics of main data capturing techniques in the construction sector [4,19,30,40,43,61,63,77,98,110,111,189,193,211–213]

Decisive features	Data capturing techniques			
	Laser scanning	Photogram metry	RFID tagging	Barcode tagging
Applicability in existing buildings	Yes	Yes	Limited	Limited
Cost	High	Medium	Medium	Low
Time	Medium	Fast	Fast	Fast
Spatial accuracy, Level of Detail (LoD)	High	High	Medium	Medium
Influence of size and complexity of the scene	High	High	Low	Low
Influence of environmental conditions	High	High	Low	Low
Importability into BIM	Yes	Yes	No	No
Data volumes	High	Medium	Low	Low
Degree of automation	Medium	Medium	Low	Low
Operability	Low	Medium	Medium	Medium
Equipment portability	Low	High	High	High
Equipment durability and robustness	Medium	High	High	Medium

4.3.2 Data processing

As functionality requirements determine the required LoD and thus the data capturing technique, functionality influences data volume, processing and related time and effort. Data processing is performed to enable the recognition of functionality-relevant BIM objects in previously captured building data, e.g. to detect installations or fittings for maintenance purposes.

During processing steps, image-based and range-based point cloud data is registered, aligned and merged into the same coordinate system [31]. This is mostly done interactively, either through defined coordinates or detected characteristics such as descriptors or tie points [31,61]. Then, data is cleaned from noise, irrelevant information and clutter [31,203] and often decimated to improve computing time. Data captured with other techniques is processed according to its data format, the required functionality and the object recognition method [25,70,110,130,194].

Applied to fulfill maintenance or deconstruction functionality requirements of complex structures, data processing might overrun reasonable computing times due to increased LoD, high data volumes or limited computing capacity of mobile devices. Further developments in computing performance of mobile devices and research in outsourcing of computing processes on cloud servers might enable faster data processing.

4.3.3 Object recognition

The captured and processed building data is used to recognize building components and their characteristics relevant to required functionalities. The recognition of objects includes object identification, extraction of relational and semantic information as well as treatment of concealments and remaining clutter [31]. Methods and tools of object recognition differ due to geometric complexity of the building, required LoD, and applied capturing technique, data format, or processing time.

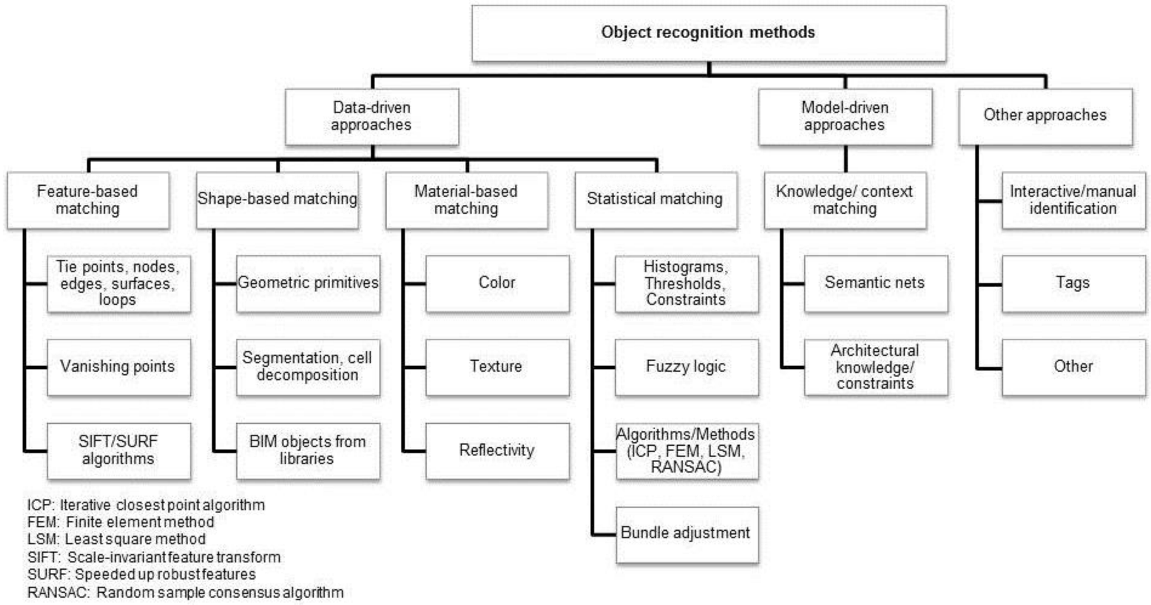


Figure 8: Systematic review of object recognition approaches applied in existing buildings [30,31,40,43,61,63,77,110,111,189,193,211–213]

Figure 8 shows data-driven, model-driven and other recognition approaches. Data-driven approaches extract building information from captured and processed data and can be differentiated into feature-, shape-, material-based and statistical matching methods. Model-driven approaches are rather based on a predefined structure such as e.g. topologic relations or constraints and perform matching of captured data through knowledge or contextual information. Other approaches include manual identification or tags. Some publications combine data- and model-driven approaches to overcome drawbacks of individual methods [62,64,65,196]. Coarse and mainly planar building components such as walls, ceilings, floors, doors, windows and clutter are recognized in small scenes of single or few rooms [62,64,65] with recognition rates between 89 and 93%. But nevertheless, research approaches try to further improve LoD and recognition rates as well as handling data uncertainty through statistical (thresholds), contextual (semantic nets, relations) or interactive (machine learning) methods [40,43,61,62,64,65,156,189,196,207].

In order to enable maintenance functionalities, detailed information e.g. on technical equipment (HVAC/MEP) [50] such as the course of ducts, installation dates, material layers or composites is necessary. This information is not automatically recognized in buildings by current approaches yet, but requires intense user input and interaction [40]. However, other industries might provide promising approaches [31,214]. Deconstruction-related LoD in recent research focus on structural components [2,24] yet, that might be recognized in image- or range-based data. But sophisticated functionalities e.g. with regard to components' connections, hazardous components, components' layers or recycling qualities demand a higher LoD that would require high analytical testing efforts and user inputs.

4.3.4 Modeling

Modeling[9] denotes the creation of BIM objects that represent building components, including both geometric and non-geometric attributes and relationships. If BIM is modeled on the basis of previously captured building information, the preceding data capture, processing and recognition methods influences data quality through the deployed technique and the provided LoD. To compare different approaches and their modeling capacities, created models might be assessed e.g. with respect to modeling or recognition accuracy, LoD or CMM[6] [31,163]. Yet, no standard BIM assessment method has been established to compare model qualities (see section 4.1.2).

[9] In this context, modeling does not refer to simulations or optimizations of processes or parameters (e.g. time or cost). Such calculations might be performed e.g. in expert functionalities on BIM data.

In practice, “as-built” BIM modeling is done interactively in a time-consuming and error-prone process [7,19,31,189], e.g. with BIM modeling software of the few major vendors Autodesk Revit and Navisworks, Bentley Architecture, Graphisoft ArchiCAD, Tekla or Nemetschek Allplan. Specialized software in the area of reverse engineering, data capture, processing and BIM modeling is analyzed in Table 8. Although some allow the rapid generation of building floor plans [130,215] or offer BIM integration, the depicted software solutions are far from automated or semi-automated BIM modeling of existing buildings.
In research, automated BIM modeling or transformations of surface models into volumetric, semantically rich entities are in its infancy [19,151]. Many reviewed publications cope with (semi-) automated modeling of building surfaces or components with respect to their geometrical representations. However, they do not regard component properties or semantic information yet [19,43,152,199,203–210,216]. If non-geometric attributes like functional, relational, economical or semantic information of existing buildings are integrated into BIM, it is done interactively or semi-automated [130,151–153]. E.g. concealed building components like ducts, pipes, conduits or plumbing (HVAC/MEP) can only be modeled with high user input yet [40]. Due to an effortful BIM creation process, model creation of existing buildings either focuses on coarse building components or is not applied yet. Besides, the high LoD, e.g. required for specific maintenance or deconstruction considerations is not compatible with current time and cost restrictions in the AEC/FM/D sector. Furthermore, our review reveals that object attributes and relations relevant for maintenance and deconstruction functionalities are not widespread modeled yet, partly due to undefined properties (see Table 4), unavailable object libraries containing older building components or unspecified LoD.
As skilled personnel and high efforts are necessary to model BIM of existing buildings, further research in automated capturing, processing and modeling could reduce building auditing cost and increase productivity in BIM-based maintenance and deconstruction processes.

Table 8: Technology analysis of commercial capturing, processing and modeling software with respect to the BIM or CAD integration

Commercial Software	Data capturing techniques					BIM Integration	CAD integration	Remarks
	Laser scanning	Photo-gram-metry	RFID tagging	Barcode tagging	Other			
Australis [217,218]	-	X	-	-	-	No	Yes	Export of DFX and ASCII
Autodesk ImageModeler [219,220]	-	X	-	-	-	Yes	Yes	Architectural application, DWG file export
Canoma [221]	-	X	-	-	X*	No	Yes	Surface texturing of CAD objects
INOVx RealityLinx Model [222]	X	X	-	-	-	No	Yes	Plant application
NuBAU freac [130,211]	-	-	-	-	X	Yes	No	Interactive creation of floorplans
PhotoModeler [223,224]	-	X	-	-	-	No	Yes	Export in DXF, textured surfaces and elevation drawings
Polyworks Modeler [225]	X	-	-	-	-	No	Yes	Import of IGES/STEP files, no architectural application yet
Geomagic Design X (Rapidform XOR2) [226]	X	-	-	-	-	No	Yes	Parametric modeling, no architectural application yet
RiSCANPro [215,227]	X	-	-	-	X*	No	Yes	Automated creation of floorplans
Vela Systems Field BIM [228,229]			X	X		Yes	No	Integrated in Autodesk Navisworks

X: Used technique
*: Digital photos

4.4 Organizational and legal issues

The use of BIM and the integrated product delivery (IPD) concept in new construction requires profound process changes [7]. As this also applies when BIM is used in maintenance and deconstruction processes, organizational issues are discussed in this section that influence the implementation of BIM in existing buildings such as collaboration of stakeholders, contractual relationships or liability.

4.4.1 Collaboration of stakeholders

Throughout the construction industry, collaboration and data exchange still is mainly document-based [48,150]. Traditionally, resistances or lack of education/training resulted in a rather inefficient collaboration [9,11,36,67,230]. Depending on the project, collaboration through BIM over the whole building LC can improve data and process management in a central information repository [30,67] and facilitate role and responsibility management through attached groupware or web services [21].

In new buildings, collaboration through BIM is increasing, especially due to improving capacities of communication media [150], such as e.g. groupware [101,102], BIM server and cloud computing [34,100,120,231,232], mobile devices [34,76,120,231–233] and augmented reality approaches [76,233]. But also the spreading of collaboration standards (e.g. Dutch VISI-Standard) and amplified training of personnel helps to overcome the implementation problems and isolated use of BIM [21,67,234,235]. Besides, requests of building owners and political pressure in some countries like UK or USA increasingly foster BIM collaboration in new construction [44,236–239].

Available BIM collaboration systems focus on functionalities of content management, viewing and reporting rather than on model creation or system administration yet, but they are further developing [150]. Nevertheless, literature still indicates prevalent social and institutional obstacles inhibiting BIM implementation in the construction sector. Often mentioned obstacles are a fragmented Architecture, Engineering, Construction, Facility Management and Deconstruction (AEC/FM/D) industry [48], resistance to changes in employment patterns and processes [48,150,240], slowly adapting training of personnel, lacking customized collaboration systems [150], as well as prevailing problems of liability, data security and interoperability [7,17,21,30,48,66,241].

For maintenance and deconstruction purposes in existing buildings, stakeholders and their roles are defined in COBie and can be linked with BIM objects for which they are responsible [50,130]. Since the majority of existing buildings are not maintained or deconstructed with BIM yet, stakeholders' collaboration might remain ineffective. Many available and partly BIM-integrated FM software solutions as well as IPD will enhance FM functionalities and collaboration. But regarding deconstruction, activities and functionality-specific process or interaction maps of BIM are not developed or implemented yet. Due to dominant time and cost restrictions in deconstruction, research focus rather on time and cost optimizations rather than on digitally supported collaboration (through BIM).

4.4.2 Responsibility, liability and model ownership

As depicted previously, collaboration systems have four major domains: content management, model content creation, viewing/reporting and system administration [150]. Especially the second domain raises most discussed topics of standard of care, contractual protection of model ownership and intellectual property, as well as of authorized uses and sensitive information in integrated project delivery (IPD) [17,48,158,239,242,243]. Insurance matters like shifting or sharing of risk as well as allocation or compensation of responsibility are also important issues [242–244].

For BIM use in new buildings, the American Institute of Architects (AIA), the Associated General Contractors of America (AGC) and ConsensusDocs are working on respective contractual guidelines [7] and are publishing contract samples [7,44,158,245]. But legal uncertainties in BIM implementation and in fee specifications in AEC/FM/D sectors [11] of other countries often remain.

As many processes in FM and deconstruction are not based on BIM yet, respective contracts have not yet been developed and standardized for these applications. Although e.g. responsibilities for hazardous materials onsite are stipulated in new construction [244], contracts need adaptation for existing buildings due to e.g. owners' responsibility for legacy. Furthermore, responsibility of model and content management during maintenance seems not to be addressed in literature and legal frameworks yet, although updated BIM content is crucial for any maintaining, retrofitting or deconstruction planning.

4.4.3 Education and Training, Culture

Although BIM is spreading in AEC industries worldwide, the need for qualified personnel remains a bottleneck of BIM implementation in new buildings [7,9,11,36,67,230]. Other major hindrances are the willingness to collaborate and cultural differences [16]. A comparative study on BIM in education identified a need for alignment of training contents, academic education and industry requirements, but relativized their statement through the rapid technological changes in this area [246].

Facility managers, owners of existing buildings, deconstructors and consultants are scarcely using BIM [15,16] and are not fully integrated in BIM development and implementation yet [15]. Thus, there is a need to enhance their integration, training and education to maintain, use and also deconstruct (if needed) the rising number of complex BIM-constructed or BIM-retrofitted buildings and infrastructures.

5 Discussion of findings and future needs

Considering BIM for existing buildings and related maintenance and deconstruction processes, we reviewed more than 180 academic and applied publications from journals, conference proceedings and other sources of professional associations, standard committees and authorities. Numerous rapid changes and recent developments not only push implementation and research in many BIM-related areas [8], but also enlarge the complexity of research. Thus, some publications or trends might have been overlooked and not been considered in this paper.

Due to the former development of BIM, architects, engineers and contractors played a major role as early adopters of BIM technology and still dominate the elaboration of BIM functionalities [15] and dissemination [7]. Although on the one hand, implementation of BIM both in new and existing buildings induces profound changes of processes and information flows (e.g. through IPD), on the other hand it accrues considerable advantages (e.g. in risk mitigation or improved data management). Recently, research turns to FM requirements, but still it is mainly focusing on new or recently completed buildings with a building information model (BIM) at hand, rather than on existing buildings without BIM [8,29]. Besides, owners, facility managers, deconstructors and related consultants are hardly involved in the BIM functionality development yet [15]. Thus, existing buildings requirements such as e.g. cause-effect and deterioration modeling [99], deviation modeling [130] or uncertainties are not considered yet.

In the following, we discuss not only major potential benefits of BIM implementation in existing buildings that could be implemented, but also challenges, process changes and resulting research gaps:

- **Functional issues:** If BIM is used for FM in new buildings, clear benefits are reported e.g. regarding improved information flows and project management, risk mitigation and positive return on investments [11] especially in complex structures. BIM in FM or deconstruction is not used industry-wide yet, but potential functionalities of BIM in existing buildings for FM [11] and deconstruction are numerous. Many FM approaches already benefit from BIM information of recently built structures e.g. through performance monitoring [7], or virtual reality [233]. Yet, only few approaches deal with deconstruction planning [2,24] or vulnerability and collapse analyses [146,154], assuming a preexisting BIM that contains the required information. But further expert refurbishment or deconstruction processes might also benefit from BIM usage through improved/supported decision-making in complex facilities, shortened refurbishment or deconstruction schedules, reduced costs, jobsite safety during deconstruction, enhanced collaboration, documentation, data management and visualizations (e.g. during bidding or renegotiations). Ecological issues are not accounted for, like resource efficiency, potentially achievable recycling qualities or recycling rates (recyclability), ability of dismantling component connections, separability of material layers and composites, deconstructions ' emissions or immissions (such as noise, dust, vibrations), or respective protection measures that could be simulated or optimized through BIM.

  If BIM is implemented in existing buildings, it might also affect sustainability ratings and certifications. Although some sustainability ratings already include some end-of-life considerations [247,248], BIM might be used to integrate monitored values such as energy consumption, waste water, or maintenance costs into their rating or to extend current assessment criteria with regard to recyclability or other end-of-life considerations on component level. These adaptions would help to enlarge the depicted environmental effects of a built structure and to verify and monitor consumption and emission values of certified structures.

As the development of maintenance functionalities requires standardized Levels of Detail resp. Development (LoD) of BIM content, COBie standard is an important milestone for BIM use in FM. Although COBie includes material and sustainability information, it excludes information on architectural parts such as slabs, walls, footing, roof, ramps and stairs that are essential e.g. for refurbishment or deconstruction planning. Also, flow segments and fittings are not included in COBie, but are relevant e.g. during maintenance, deconstruction and separation of components and materials. For deconstruction-related functionalities no LoD is defined yet, and process and interaction maps for information exchange in BIM are lacking. This is hampering interoperability and information exchange in 'as-built' BIMs. Besides, the many coexistent concepts for assessing BIM model quality (e.g. LoD, Object/Element Matrix, or CMM) might benefit from harmonization.

Although the use of BIM in existing buildings might contribute to better project and data management, it is confronted with major shortcomings. As BIM use in existing buildings is only appropriate with precise, unambiguous and relevant up-to-date information [3], BIM data quality is crucial to any applied functionality. Major challenges and areas of research are therefore on the one hand the initial data capture and automated BIM creation [62,63,151,152] (see section 4.3) and on the other hand the information maintenance and assessment in BIM [7,11,21] (see sections 4.1.2 and 4.4). A third major issue is the handling and modeling of uncertain data, objects and relations occurring in existing buildings, which is not addressed in BIM yet. To cope with these issues and to reduce time and cost, the integration of monitoring and capturing methods into BIM seems promising to keep BIM information automatically up-to-date. Further development of attributes and integration of techniques like semantic reasoning is essential to provide unambiguous attribute definitions and to improve the capture and processing of building information, allowing future FM and deconstruction functionalities. This will help to ensure interoperability between BIM and attached expert functionalities and to facilitate BIM implementation in existing buildings.

- **Informational issues:** Incapable interoperability still is a major obstacle in BIM data exchanges both in new and existing buildings. To increase interoperability, universal data structures are developed continuously. But developments focus on new rather than existing buildings and their requirements yet [180]. Some developed concepts (IDM, MVD) were recently specified for expert functionalities in new or recently constructed buildings, e.g. for energy analysis or for FM. But to enable data exchange with e.g. potential decontamination planning or deconstruction progress tracking functionalities, both concepts require further specifications. Besides, MVD are not available for the actual IFC2×4 format yet [249]. As long as research focuses on recently built structures and their requirements, the development of standards will be slow and hamper BIM implementation in existing buildings.

  The second informational challenge results from the outpacing BIM technology development. Due to long lifetimes of buildings and infrastructure, challenges arise from interoperability within the rapidly developing BIM models, expert functionalities and continuous model maintenance during building lifetime [11,12,37]. Besides, due to increased demand for semantic web technologies [12,67,179], mobile BIM and cloud computing [34,120,231,232] that further enhance applicability of BIM, challenges are to be met in management of temporal data, transaction management and synchronization in BIM [11,12,37,150].

- **Technical issues:** If building documentation is inadequate for maintenance or deconstruction processes, capturing and surveying techniques with different qualities are applied to audit and gather existing buildings' characteristics. The functionality-related Level of Detail (LoD) and the corresponding data capturing technique influence all following steps of BIM creation and its associated effort, e.g. surveying and processing times [4].

Due to a mainly interactive and time-consuming data capturing, processing and creation process, BIM modeling effort is high and thus BIM is often not applied in existing buildings yet. Besides, a high LoD e.g. required for detailed maintenance or deconstruction considerations is not compatible with current time or cost restrictions in the AEC/FM/D sector.

Resulting major research challenges are (1) effort reduction (automation) of capturing, processing, recognizing and 'as-built' BIM creation anew [4,31,43,45,62,77], (2) capturing and integrating semantic information into BIM [6,43,45] as well as (3) addressing of technique-specific restrictions e.g. such as environmental influences in field operation [64,130] or post-processing of concealed, distorted, structural or semantic building information [19]. Therefore, approaches focus on the development of cost-efficient and highly automated BIM creation based on laser scanning or photogrammetry. But future research approaches could also include material- or texture-based recognition [151] and non-destructive testing methods such as ground penetrating radars, radiography, magnetic particle inspection, sonars or electro-magnetic waves [205] or tags installed during retrofits to increase information richness in BIM. Further automation of modeling semantic and volumetric BIM objects from captured data [6,43,45] might be achieved through specific but yet unavailable object libraries of real building components, learning algorithms [31], testing in real environments [31,66], consideration of uncertainties, and further detailing through capturing small, concealed or non-planar components in complex buildings [31,82,190]. The recognition and modeling of installations, ducts and pipes (HVAC/MEP) might e.g. benefit from similar approaches in other industries [214,222]. Apart from that, BIM applications on mobile devices are increasingly demanded, but yet face high data volumes and computing times [64,130].

- **Organizational and legal issues:** With the spreading of BIM in the AEC/FM/D communities, traditional processes and stipulations are adapted at different speed and scope to digitally supported collaboration through BIM. Political pressure in countries like UK or USA furthers implementation of BIM [236,237] e.g. through public tendering, while developments in other countries' construction sectors are lagging behind. Thus, organizational and legal BIM frameworks vary in different countries and in application in new or existing buildings, but different stages of development are not reported or examined in literature yet.

  Although some sources describe a lacking industry-wide collaboration due to resistances and lack of training [7,11,67], BIM collaboration is spreading [150]. Recently, capable collaboration systems are developing [150] yet focusing on content management, viewing and reporting rather than on model creation or system administration. And further capacity developments in this area are expected to facilitate BIM implementation e.g. through cloud computing, sensor networks or semantic web approaches [150,179].

  As BIM implementation demands profound process changes [7], it has great implications on contractual relationships in AEC/FM/D industry. In recent years, legal instruments and contractual agreements in the AEC/FM/D industry on BIM were not widely adapted [130,153,250,251]. But lately, institutions and professional associations in leading countries provide contract templates and legal advice for stakeholders in new building projects. As stakeholders, their interests and required processes (e.g. bidding and procurement) vary from planning and construction to maintenance and deconstruction LC stages, adaption of legal frameworks would be necessary if BIM is applied in existing buildings. Besides, an interdisciplinary education of facility managers, deconstructors and consultants might be necessary to implement BIM in existing buildings. But as long as issues of model ownership and data responsibility, LoD, liabilities and fees are not stipulated or standardized [11], it will hinder BIM implementation in existing buildings due to reduced data security and user confidence [17].

6 Conclusion

The conducted literature review of over 180 publications presented the state-of-the-art implementation and research of building information models (BIM) in existing buildings with focus on maintenance and deconstruction LC stages. Due to the former BIM development, architects, engineers and contractors play a major role as early adopters of BIM technology and still dominate the elaboration of BIM functionalities [15] and BIM dissemination [7]. Despite the increasing BIM usage in new structures, implementation of BIM in existing buildings is still limited yet, focusing on recently completed buildings with a BIM at hand rather than on existing buildings without BIM [8,29]. But research approaches are intensifying to harness BIM for application in existing buildings and to capture and integrate building data into BIM. A growing number of maintenance interfaces and functionalities in preexisting BIM are developing for recently constructed buildings, while applications and research approaches for deconstruction functionalities in BIM remain rare and do not cover all related aspects. Owners, facility managers, deconstructors and related consultants are hardly involved in BIM functionality development yet [15].

Although on the one hand, implementation of BIM both in new and existing buildings induces profound changes of processes and information flows (e.g. through IPD), on the other hand it accrues considerable advantages. Potential BIM functionalities and benefits in existing buildings are numerous. Calculation of alternatives and optimizations seem promising to enhance project management and risk mitigation or to limit costs and duration of FM or deconstruction measures, e.g. in complex buildings or infrastructures. Onsite progress tracking, measurements and monitoring through cloud computing depict potential future trends of automated capture and transformation of building information into BIM. Besides, stricter regulations on rubble management and increasing product responsibilities of manufacturers might lead to BIM-based monitoring of (hazardous) components and to increased interest in information on existing buildings, related sustainability properties, reuse/recycling options or emissions (e.g. through LCA). Other important FM and deconstruction requirements such as e.g. cause-effect and deterioration modeling [99], deviation modeling [131] or uncertainties are seldom considered yet. To implement such functionalities, a structured and integrated data repository on building information like BIM could be beneficial to authorities, decontaminators, deconstructors or industry professionals.

Our findings reveal that major challenges and areas of research are (1) the automation of data capture and BIM creation (without preexisting BIM), (2) the update and maintenance of information in BIM and (3) the handling and modeling of uncertain data, objects and relations occurring in existing buildings in BIM. New data capturing techniques try to overcome lacking building information at low costs. But current approaches face challenges of capturing structural, concealed or semantic building information under changing environmental conditions and of transforming captured data into unambiguous semantic BIM objects and relationships. Less dominant challenges are varying quality assessments of BIM models, undefined LoD for deconstruction functionalities, interoperability between BIM models of different generations and underdeveloped object properties and processes for maintenance and especially deconstruction purposes.

Adaptation of BIM-related legal and organizational frameworks differs between countries. Progressive AEC/FM/D industries (e.g. UK, USA) reformed national regulations and implemented novel collaboration processes through BIM, but rather for new than for existing buildings. Organizational and legal issues seem to be major levers to influence BIM implementation due to their coherences of BIM in a broader sense. But to our knowledge there is neither research on the worldwide spreading of BIM and its related changes of processes and regulations in different circumstances nor a comprehensive cost-benefit analysis of BIM implementation for existing buildings yet.

Fast developments of BIM and the recent release of standards such as COBie or IFC 2×4 are promising for future process automation, alignment of BIM with AEC/FM/D processes and efficient resource management through BIM in new and existing buildings. Longtime trends like the increased digitalization and automation, growing existing building stocks and sustainability requirements, as well as emerging technologies like cloud computing, semantic web technology and mobile BIM devices will stimulate and extend BIM implementation in existing buildings. But due to the revealed state-of-the-art BIM implementation in existing buildings, this area has many challenging future research opportunities at hand.

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